4.3   MICROLITHOGRAPHY & MASK MAKING
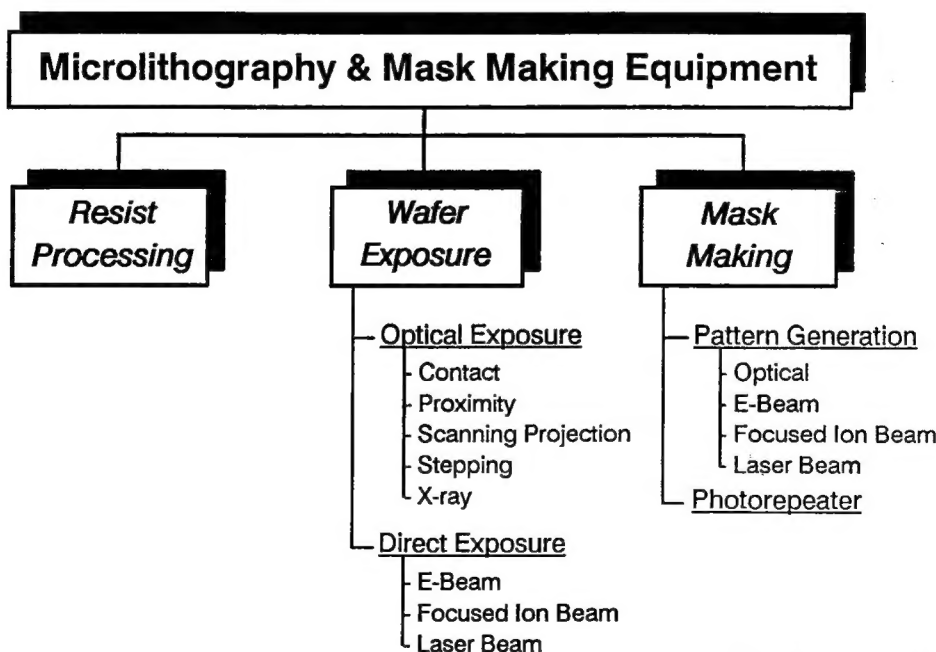
4.3 MICROLITHOGRAPHY & MASK MAKING

- **Lithography equipment is used to pattern circuits on wafers.**

- **Its key market segments are resist processing, wafer exposure, and mask making.**

- **A brief overview of each type of equipment follows.**

There are two essential applications for semiconductor lithography equipment. They are lumped together here under the name 'microlithography and mask making'. The two segments consist of mask-making equipment and wafer patterning equipment. Both have a common origin in the early step-and-repeat cameras which were used to manufacture masks which were, in turn, used to selectively expose photoresist coatings deposited on the surface of a semiconductor wafer.

The microlithography equipment market consists of three sub-segments: resist processing equipment, wafer exposure equipment, and mask making equipment. These three segments and their various sub-segments are shown in the family tree chart in Presentation 4.3.0-1. All three segments serve in some manner to aid in the transfer of a pattern to the integrated circuit via a light sensitive material called photoresist. The purpose of photoresist is to serve as a protective coating which can be used to se-

Presentation 4.3.0-1

Microlithography & Mask Making Equipment

Resist Processing

Wafer Exposure
- Optical Exposure
  - Contact
  - Proximity
  - Scanning Projection
  - Stepping
  - X-ray
- Direct Exposure
  - E-Beam
  - Focused Ion Beam
  - Laser Beam

Mask Making
- Pattern Generation
  - Optical
  - E-Beam
  - Focused Ion Beam
  - Laser Beam
- Photorepeater

Source: VLSI RESEARCH INC
2244-366D

lectively protect substrate surfaces (the wafer) from subsequent etching or sputtering.

The key factors that drive lithography equipment are its ability to resolve and control images in photoresist. Lithography is a multistep process that involves making the mask, depositing the resist, exposing the wafer, and developing the resist. Manufacturing a semiconductor typically requires 15 or more of these processes to complete a device. Presentation 4.3.0-2 depicts microlithography and masking equipment flow processes. The following paragraphs will describe this equipment grouping in more detail.

Resist processing equipment is used to apply a thin film of photosensitive resist before exposure, and afterwards, to develop the pattern in the resist. This is typically done by pouring liquid photoresist or developer on the wafer and spinning it. These spinners are the heart of this equipment, which is why equipment is also commonly called 'spin gear.' It is also referred to as 'Track'. Critical factors that affect resist processing equipment are uniformity, adhesion, edge bead removal and contamination control. Vendors are continually addressing these factors and are enhancing their resist processing equipment accordingly.

Wafer exposure equipment is at the heart of the lithography process. This equipment prints the circuit pattern onto the wafer by selectively exposing the resist to light, electrons, or ions. The key criteria driving the exposure equipment market are linewidth, registration, and depth of focus. An ability

Presentation 4.3.0-2

Microlithography & Mask Making Process Flow Chart
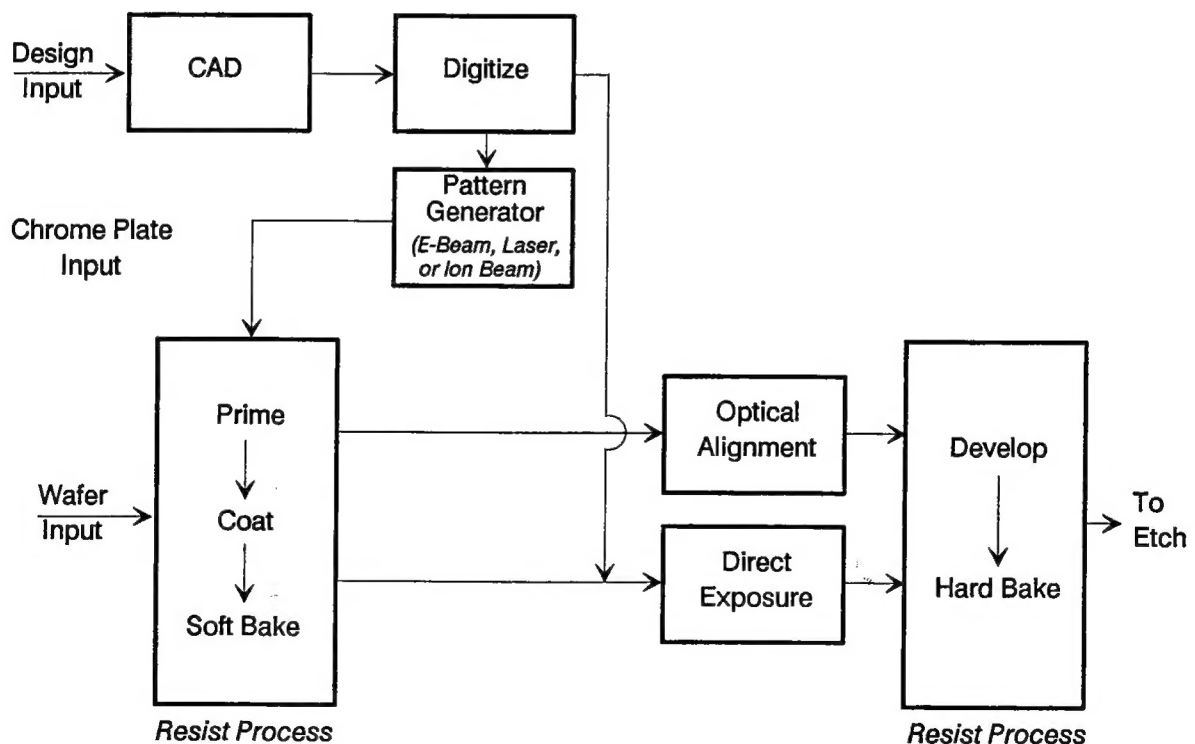
Source: VLSI RESEARCH INC
2244-367D

to decrease linewidths adds value by lowering cost, increasing the number of die produced and by increasing device speed. Registration helps to determine linewidth and it helps to increase device speed by accurately overlaying one layer upon another. Depth of focus control helps to determine CD control and therefore device speed.

Wafer exposure equipment consists of two basic categories: Alignment and direct exposure equipment. Alignment equipment consists of contact, proximity aligners, scanning projection aligners (both standard and DUV light sources), stepping projection aligners and X-ray aligners. Section 4.3.1 will describe these classes in greater detail. For the purposes of this introductory section however, they can all be considered as 'optical' aligners. This designation is being used in the restricted sense that optical alignment equipment makes use of photons to expose photoresist.

Originally, all optical alignment methods were of the 'contact' type; meaning that patterns were imaged and exposed in a photoresist via a mask which was in intimate physical contact with the upper surface of the photoresist. Contact exposure created yield degrading problems, for the contact caused mask scratches and resist lift. Subsequent equipment developments successfully moved the mask slightly away from the upper surface—such that it was in the 'proximity' of the surface, but not quite touching it physically. This meant a distance from between about 15 to about 80 microns. Next, equipment was developed that was able to project an image of the mask onto the wafer surface just as slide projector does. Further development lowered the wavelength of the light progressively away from the 'optical' light regions and towards the 'near' ultraviolet region, then further still to the 'deep' ultraviolet region, and eventually to X-ray.

With **contact exposure** techniques, the mask rests directly on the resist while the wafer is being exposed. The pattern is exposed by using the mask to 'stencil' the image on the wafer. This method is generally limited to resolutions above five microns. Contact printing gives excellent contrast at pattern edges, but the direct contact of the mask and wafer damages both mask and photoresist, which lowers yield. Consequently, contact aligners are in limited use today.

Proximity printing is similar, except that the mask is held slightly above the wafer surface during exposure. In comparison to contact printing, this method increases yield, but decreases resolution due to penumbral blur and diffraction. Consequently, proximity aligners are also used infrequently today. However, they have come back into popularity for X-ray lithography research.

Scanning projection exposure is also an older method. These systems differ from contact and proximity aligners in that the image is projected onto the wafer surface. This offers much better resolution and yield than contact or proximity aligners. It also offers high throughput. Its key limitation is that it does not offer the registration accuracy of a stepper.

Steppers are the standard wafer exposure system in use today. These machines expose a wafer on a field-by-field basis using a step, expose, and repeat method. This method offers better alignment accuracy and focus control by aligning and exposing only a portion of the wafer at a time. The image can also be reduced from a larger mask, offering increased resolution and yields. Improvements in masks, lenses, light sources, numerical aperture, focus control, and registration continue to extend the optical stepper's ability to pattern wafers.

X-ray aligners are steppers that use X-rays' and proximity techniques to obtain higher

resolution in an R&D environment. Wafers exposed with X-rays show very high edge contrasts, and low defect levels. This equipment has lower defect levels because X-rays pass through most particulate contamination. However, there are many technical problems that limit their use.

Direct Exposure equipment exposes the photoresist directly, without using a mask. This is done dynamically with moving pencil-like beams of particles—electrons, ions, or photons. The first of these three approaches, and the most commercialized version, consists of electron beam direct-writing systems. These expose the photoresist directly via a stored pattern. An electron beam is accelerated onto the photoresist in a manner similar to the acceleration of an electron beam of a conventional cathode ray tube. The stored pattern is used to turn the beam on-or-off as it scans the wafer surface. Several variations of this basic theme exist. Still, the machines are fundamentally alike and belong to a single class of direct exposure systems whose purpose is to bombard the photoresist with electrons.

Ion beam is the second category of direct exposure equipment. It consists of direct writing systems and focused ion beam projection systems. FIB systems can be similar to E-beam systems or either optical systems. Both systems focus ion beams on the wafer. This is the base from which the popular acronym FIB was derived.

The third method of exposure involves the use of a laser beam to expose photoresist. **Laser beam** direct exposure equipment uses light, just like other 'optical' aligners, but it is fully coherent and focused into a narrow beam. Laser Beam systems differ somewhat from E-beam and FIB systems. First, the beam need not operate in a vacuum and is therefore less costly to operate. Second, the laser beams tend to be more stable and therefore offer better registration.

Mask making involves the transfer of specific CAD designs into a physical layout to create a geometrical pattern. After the mask layers have been created by a CAD system, they must be reproduced as the circuit's actual image on chrome-glass. The initial layout may be magnified several times and can be several square feet in size. The first step in the reduction process is done by way of digitizing. The coordinates of the IC layout are digitized and stored on tapes. The pattern is then transferred onto the surface of chrome-quartz plates. Four basic methods are employed in the latter process. They are: optical pattern generation, electron beam (E-beam) pattern generation, laser pattern generation and ion beam pattern generation. These four equipment segments and image repeaters—or photorepeaters as they are sometimes called—compose the mask making market. Photorepeaters are used to make multiple reproductions of the reticle pattern on a mask. This process is described in the following paragraph.

The reticle is first made via the pattern generation system which makes use of these stored patterns to drive a computer controlled beam, thus exposing the resist. It first reads the tape, then directs the beam to expose the reticle with the same pattern as the original IC layout. When multiple reproductions of the pattern are required on a reticle or die—the patterned reticle can be transferred to another reticle or mask by a photorepeater. To do this, the reticle is exposed to an area of the blank mask and then moved (stepped) to the next location to be exposed. It then repeats the process. When the step and repeat operation is complete, the plate is developed into a master mask plate. Several submaster masks can then be produced from the one master mask. These later steps are typically done on older designs where high precision is not required.

In E-beam, laser, and ion beam mask making, the data on the tape is used to direct a beam onto the photoresist, rather than to move a variable aperture. The two key advantages with the process are:

- Elimination of alignment concerns
- Elimination of image deterioration

Notes

4.3.1 *CURRENT INDUSTRY CHARACTERISTICS*

4.3.1 CURRENT INDUSTRY CHARACTERISTICS

4.3.1 CURRENT INDUSTRY CHARACTERISTICS

- **It is the largest semiconductor equipment market.**

- **This market is notable for its high rate of competitive turn-over.**

- **Steppers dominate wafer exposure technology.**

- **Optical systems remain viable into the foreseeable future.**

Microlithography equipment has historically been characterized as being the queen of the clean room. Wafer exposure equipment has, by far, the most stringent precision requirements of all—generally needing to resolve lines and spaces below one micron in width. These must often be overlaid thorough twelve or more layers—requiring alignment accuracies of better than 0.15 microns across a six or an eight inch wafer. This is about the equivalent of getting a hole-in-one from an eighteen mile drive. Such requirements for precision have stimulated a high degree of automation in microlithography equipment.

Simultaneously, integrated circuit yield losses are closely correlated to particulate contamination at or in the vicinity of the lithographic equipment. This has further stimulated automation, cleanliness and error-free operation. Consequently, modern lithographic systems tend to exist as 'islands' in a wafer fab area. Prices of individual pieces have risen from a few tens of thousands of dollars about two decades ago to between two and four million dollars today. A totally outfitted lithographic area contains an investment in the high tens-of-millions of dollars.

As the industry has evolved, only a few suppliers have been able to sustain the development efforts needed to successfully produce machines of this class. So the industry has coalesced into one dominated by three or four suppliers. Nikon, and Canon dominate the wafer exposure market while ETEC dominates the mask making market. These suppliers are plagued by rapid ups-and-downs in the market as the industry continually adjusts to such large-scale investments.

This section will outline these effects upon the development of the industry and will document the technology driving it.

4.3.1.1 Development of the Lithography Industry

Since the patterning of the first IC, advances by the semiconductor industry have largely been the result of continuous development of lithography equipment. These advances are what made Moore's Law possible. All lithography operations—resist processing, wafer exposure, and mask making—evolved out of the photographic process to serve the needs of manufacturing semiconductors. These procedures are all inter-related and together they make up the overall lithography industry.

Microlithography and mask making equipment usage dates back to the mid-fifties and to the development of the diffused mesa transistor. That structure was one of the first to make use of thermally grown silicon oxides in conjunction with a photoresist followed by an etch. Still, it was the subsequent development of the planar transistor at Fairchild, in 1953, that was to provide the impetus for growth and pave the way for integrated circuit development. Since then, both integrated circuits and alignment equipment have developed together in a hand-in-glove fashion. It is unquestionably safe to say that modern VLSI and LSI circuits would not have developed as rapidly without simultaneous improvements in microlithography and mask making equipment.

4.3.1.1.1 Development of the Resist Processing Industry

Most of the attention in microlithography has been focused on aligners. For many years resist processing equipment was considered to be merely a 'gooey' necessity to the more important task of wafer exposure. If the resist was deposited uniformly on the wafer, the equipment had fulfilled its needs in lithography. The key equipment drivers were reliability, low wafer breakage, and an ability to withstand the photoresist that always worked its way into systems and gummed up mechanisms.

For this reason, early resist spinners were very simple. Like virtually all manufacturing procedures in the sixties, resist processing was manual. Spinners consisted of a motor, spindle, and vacuum chuck. Resist was dropped on the wafer from a bottle. Resist developing and baking was also done manually. Developing was done in a tank of developer and baking was done in industrial ovens. Headway Research was one of first companies to offer such equipment. Pre-

sentation 4.3.1.1.1-1 shows Headway Research's spin system.

By the early seventies, resist processing was becoming an integral part of the equipment industry. The first automated systems were coming out on the market. These systems offered automatic in-line clean, spin, bake, develop and bake stations with cassette-to-cassette inputs. The first company to offer automatic resist processing equipment was IMS. It was soon followed by II Industries. IMS was acquired by GCA and gave rise to its famous wafertrac system that used an air bearing to transport wafers (see Presentation 4.3.1.1.1-2). II Industries was absorbed into Kasper Instruments which was in turn absorbed by Eaton Wafer Systems.

Both of these companies enjoyed enormous success at being the first to offer automatic systems. By 1974 GCA dominated the market with a 38% share (see Presentation 4.3.1.1.1-3). Kasper was the second largest supplier. At $4.2M in sales, the market was still extremely small. But by 1979, the market had blossomed to $63.5M. GCA and Eaton held a combined share of 61% (Presentation 4.3.1.1.1-4). Such rapid growth was attracting significant competitive attention by the early eighties. Dainippon Screen had emerged in Japan; Cobilt and Silicon Valley Group had entered the market in the United States; Censor and Convac had entered the market in Europe; and TEL was emerging as a significant player in Japan.

The trend to factory automation was also a key driving force in the late seventies. GCA and Eaton developed track systems which offered designs for fully automated track systems throughout a wafer fab. This equipment offered computer control, direct hook-up to aligners, and the ability to create automated islands with multiple tracks feeding lithographic systems. But these early automated systems were unreliable
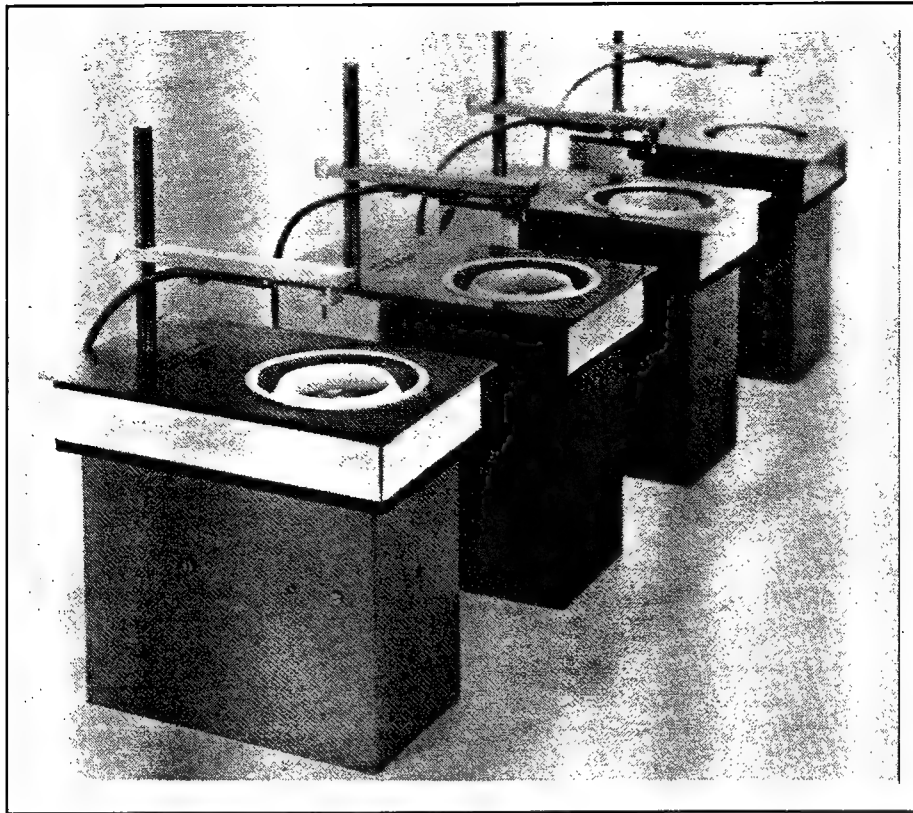
Presentation 4.3.1.1.1-1

Headway Research's Resist Spinner

and prone to contamination. While GCA and Eaton dominated the market in the late seventies new competitors were emerging to take advantage of their weaknesses.

Silicon Valley Group was the most prominent new entrant at the time. It was formed from a group of executives that left Kasper after it was acquired by Eaton. SVG's business strategy was to design a more robust and reliable system. Its System 80 is shown in Presentation 4.3.1.1.1-5. On the surface, it looked the same as other resist processing systems. But details such as an easy-to-clean, pressure sensitive keyboard and handles on the ovens for easy removal showed a more thoughtful design. SVG was one of the first equipment companies to do extensive subsystem testing.

They were also the first company to use stainless steel cabinets. In all likelihood, they were the first wafer fab equipment company to use ATE to test boards. Inside their factory they had the simple slogan "Do it RIGHT the FIRST TIME." At one of SVG's first SEMICON/West show's, the system ran for the full-three days without breaking a wafer. At an early shoot-out against Eaton inside National, their system turned on immediately. Eaton's system did not become fully operational until one week after SVG had won the order.

Around 1982, stories of phenomenal yields in Japan began to make contamination the hottest issue driving resist processing. There were many issues to be addressed. It was found that the photoresist that was

"The patented GCA air bearing floats wafers free of backside contact."
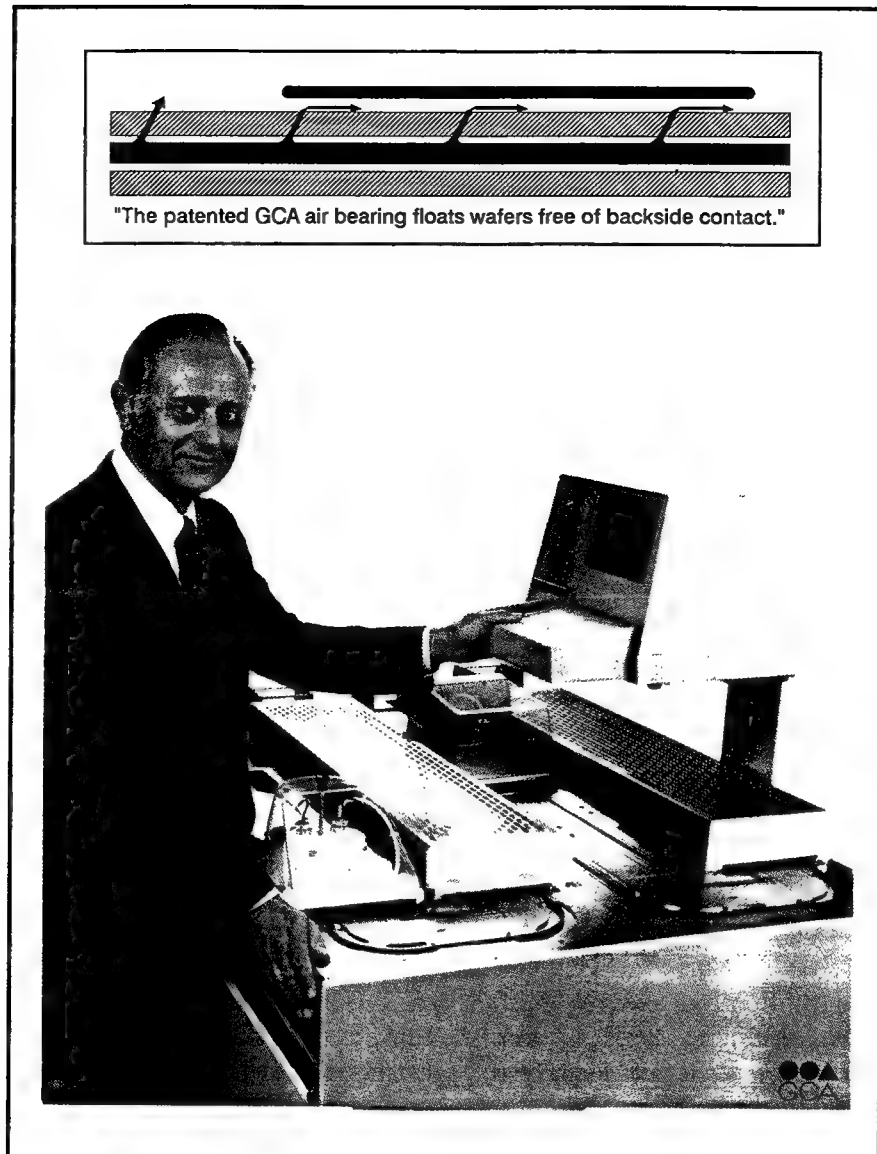
Source: GCA
2244-369

Presentation 4.3.1.1.1-2

GCA's Wafertrac™

always gumming up processing equipment was finding its way back on wafers. Air track was found to blow contamination from tracks onto wafers. Mechanisms above the wafer plane showered them with metallic particles. Dainippon Screen and TEL had solved these problems, but their systems were not being imported. This issue was particularly important on the east coast and southwest where American companies were still producing DRAMs in large volumes.

Machine Technology developed their Omni-chuck and later, their Multifab system to solve this issue. Prior to this MTI had been known mostly for scrubbers and hot plates.

Presentation 4.3.1.1.1-3

1974 Resist Processing Equipment Market
(worldwide sales in $M)
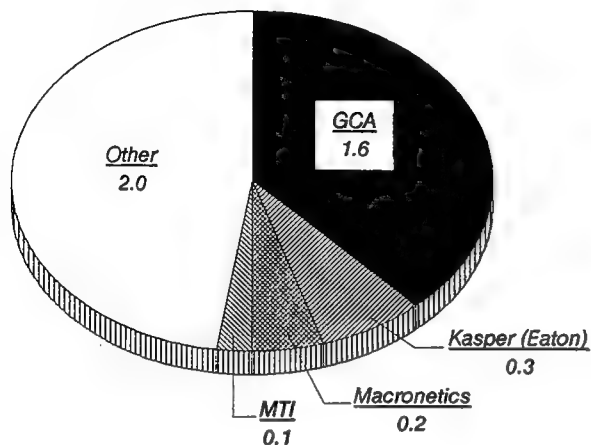
1974
Total Sales = $4.2M

Source: VLSI RESEARCH INC
2244-370G

Presentation 4.3.1.1.1-4

1979 Resist Processing Equipment Market
(worldwide sales in $M)
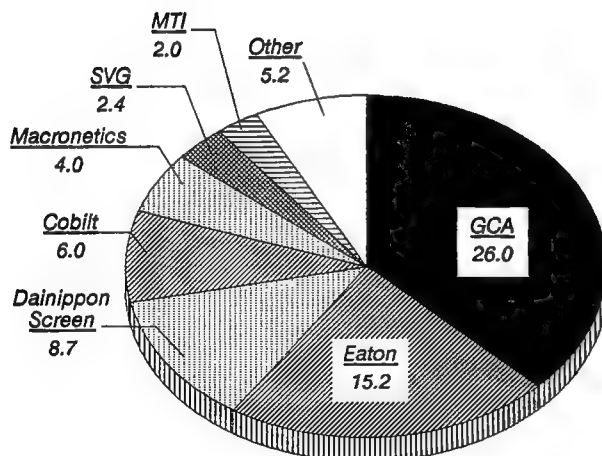
1979
Total Sales = $69.5M

Source: VLSI RESEARCH INC
2244-371G

But MTI would soon become known as the most creative company producing resist processing equipment. The Omnichuck was the first new system architecture since GCA had developed the first integrated system. It offered significant reductions in footprint and was a first stab attempt at yield improvement. But the company really gained momentum with its Multifab. It was the first system to fully eliminate belts and air track—a major source of contamination. Its process cup spun in order to quickly carry-away excess liquids, giving it the first edge bead process without splash-back problems. Its develop module was also innovative in its use of an ultrasonic nozzle to create a vapor of developer for greater uniformity. MTI was also the first equipment company to use a surface particulate scanner to certify every system they shipped. These efforts paid off for MTI and its customers. One company noted yields increased from 47% to 56% on 64K DRAMs after switching to MTI's Multifab resist processing equipment from conventional track.

In Japan, Dainippon Screen (Screen) was capturing substantial portions of the market. Its strategy was similar to SVG's though the technology was older. Nevertheless, it was extremely reliable. Screen track has a reputation for being virtually unstoppable to this day. They were able to reduce contamination by focusing on the details of the system. This, combined with Screen's process knowledge made them very strong in Japan's market.

By the mid-1980s, there were major shifts in market leadership. While SVG and MTI were carving up the western and eastern states; Screen and a rapidly emerging TEL were eliminating all foreign competition in Japan (see Presentation 4.3.1.1.1-6). GCA and Eaton would never recover. Japan's massive capital investments would eventually propel Screen and TEL to the top two positions in the world. SVG was to become

Presentation 4.3.1.1-5

Top View of SVG's System/80

Module Index Station
2" (50mm) to 5" (125mm) diameter wafers can be accommodated in either 25 wafer cassettes with 3/16th of an inch spacing or 20 wafer cassettes at 1/4 of an inch spacing. Either single cassette or dual cassette load or unload can be specified. Only mechanical adjustments are required when changing size: no electronic adjustments are required.

System/80 Control Module
Each module controls the wafer movement on the track and the process occuring at that track. Inside each module are 2 logic P.C. boards—CPU Board and a Track Interface Board (Analog functions). There is no other control logic in the system. Both the P.C. boards and unit's Control Module can be quickly replaced. Each independent Track Control Module can store 9 process programs, each with a maximum of 4 events each. Diagnostic readout for each track is visible on the Control Module Keyboard. The keyboard is flat and sealed with a solvent resistant film.

System/80 Coater
With SVG's specially designed collinear motor system, photoresist dispense or spindle rotation speed can be programmed down to 100 rpm. Only SVG offers such low speeds without sacrificing the high speeds (up to 9,500 rpm) used for spinning dry. The dispense bar swings to one side for access to the solid Teflon® catch cup. The photoresist dispense and drain system are Teflon® and stainless steel.

Oven Interface
As the wafer exits from the track on the interface, the interface belt speed first adjusts to the carriage belt speed and then the interface belt speed changes to the programmed oven belt speed.

IR Oven Temperature Controls
Oven temperature is controlled by Barber Coleman's microprocessor controllers with digital readout and deviation indication from set point.

System/80 Oven
The single element design with multiple zones (similar to a diffusion furnace design) has greater uniformity than other IR ovens which integrate multiple elements. Either 36 inch or 48 inch element lengths are available. A choice of top, bottom, or both top and bottom element placement provide the engineer with versatility of design. The wafer is transported on stainless steel conveyor belts. A heating tunnel of Vycor® panels give flat zone uniformity of ± 2° C.

Multiple Function Index Stations
Every index station can be selected in any of these three modes:

Sender
Receiver
Pass-thru

Cabinet Construction
Solvent resistant painted sheet metal cabinet panels either lift off or swing up for access to the track and oven.

Source: SVG
2244-372

Presentation 4.3.1.1.1-6

1984 Resist Processing Equipment Market
(worldwide sales in $M)

1984
Total Sales = $153.7M

Source: VLSI RESEARCH INC
2244-373G

the third largest followed by MTI. GCA would eventually exit the market.

The late 1980s saw another revolution of sorts in the resist processing market. As the number of process steps continued to increase, the demand for resist processing equipment increased and, in turn, prices rose. Resist processing equipment became increasingly complex to meet manufacturing demands. This caused prices to increase by more than five times during the eighties. End-users began to require more modules in track systems which translated into higher costs. Resist processing systems sold for roughly $120K in 1980. By 1989, they were selling for as much as $650K. Higher ASPs and increased demand caused the resist processing market to grow at a CAGR of nearly 20% from 1984-1989.

4.3.1.1.2 Development of the Wafer Exposure Industry

The development of the wafer exposure industry has been one of the most competi-

tive and tumultuous in the equipment industry. This is largely because lithography has always been one of the most lucrative markets in wafer fabrication. Lithography equipment has continuously made possible dramatic reductions in cost-per-bit by reducing linewidths, and increasing yield. The market boomed for equipment makers because with these gains came higher equipment prices and lower throughputs.

The intensity of competition and the technical demands of this market have meant that no single company has been able to retain leadership for more than one generation of equipment. Additionally, no company has ever regained its lead after losing in the lithography market.

The sixties was a very active decade for lithography. The advent of the IC and the realization of the impact it would have sparked extensive research. It was already known that lithography would be the key to IC manufacturing technology and that reducing linewidths would be the main drivers. One landmark technical paper titled, 'The Silicon Insulate-Gate Field-Effect Transistor' by S.R. Hofstein and F.P. Heiman set off a frenzy in the semiconductor industry to reduce linewidths. This paper was the first to prove that by decreasing linewidths, yields would increase.

This frenzy was so great that AT&T and RCA established their own research programs in X-ray lithography soon after Hank Smith invented it at MIT, thus predicting the trend to shorter wavelengths long before it was ever practical to use X-ray in production.

Direct writing techniques were also researched in the sixties for use in both mask making and as an alternative to mask exposure. The advent of scanning electron beam microscopy created an impetus for the use of electron beam systems in exposure. The earliest work in E-beam systems appears to

have begun in Europe. By the mid-sixties, both Cambridge University and the University at Tubingen had demonstrated such equipment. Commercial research began shortly thereafter at many industrial labs. Cambridge and JEOL had begun commercial E-beam direct write programs by 1969.

Nevertheless, contact aligners were the first practical exposure systems to be developed for manufacturing in the early 1960s. Microtech, Electroglass, and Preco were the first companies to offer them. In 1962, Kulicke & Soffa took the industry by storm. Its Model 682 contact aligner quickly displaced these existing suppliers. Nearly 300 units were installed throughout the product's lifetime. K&S's success continued when in 1965, the Model 686 contact printer was introduced. Some 1800 units were shipped over its lifetime, at an average selling price of $8,500. These systems made Kulicke & Soffa the most successful equipment vendor of that time.

By 1972, the need for a new generation of aligners had become clear. In the previous year, Mostek had introduced the 4K Dynamic RAM while Intel introduced the first microprocessor—the 4004. Large scale integration of more than ten thousand transistors was now a production reality. At that time, Kasper was making serious inroads into the lithography market with an improved contact aligner. Kulicke & Soffa had combined efforts with Cobilt to work on what was eventually to become Cobilt's soft contact aligner. Nevertheless, contact aligners were not destined to make serious inroads into LSI manufacturing.

Contact printers can actually perform fine-line lithography and can achieve one micron patterns. But this occurs at a terrible loss of yield for large die sizes. However, in those early days, fine-line microlithography (one micron) wasn't necessary for integrated circuits, though yield improvement was.

So by the early seventies several companies had begun to experiment with non-contact printing methods. Kasper Instruments was one of two companies to offer the first non-contact aligners. They introduced the proximity aligner in 1973 (see Presentation 4.3.1.1.2-1). In this printing mode, the mask supposedly does not come into intimate contact with the wafer. Instead it is held about 75 microns (3 mils) above the upper surface. Resolution was poorer—roughly 4 to 6 microns was about the narrowest line-width that could be achieved—but yield improved. However, Kasper's proximity method was not accepted by industry in those early days because it was never able to control the gap spacing.

At about the same time, history was to repeat itself when projection aligners appeared on the scene. The similarities between Perkin-Elmer's emergence and that of Kulicke & Soffa's are striking. Perkin-Elmer's optical group, while working in conjunction with Intel, developed the first practical scanning projection system in the early seventies. Presentation 4.3.1.1.2-2 shows Perkin Elmer's Micralign. It had evolved out of projection techniques researched by Perkin Elmer and the military. A team of four key engineers brought it to life: Abe Offner, Jere Buckley, David Markle and Harold Hemstreet. The first system was shipped in 1973—one decade after Kulicke & Soffa's first shipment of aligners. K&S would soon exit the aligner market.

While, Perkin-Elmer's success was significant as measured by sales, its penetration into the majority of fabs was not immediate. It, too, had difficulty in being accepted until several years of trial and error had passed. Heavy involvement in training finally succeeded in providing users with adequate understanding and helped to overcome the initial hesitance. By 1976, the system had proven its success and Perkin-Elmer found themselves virtually without competition and
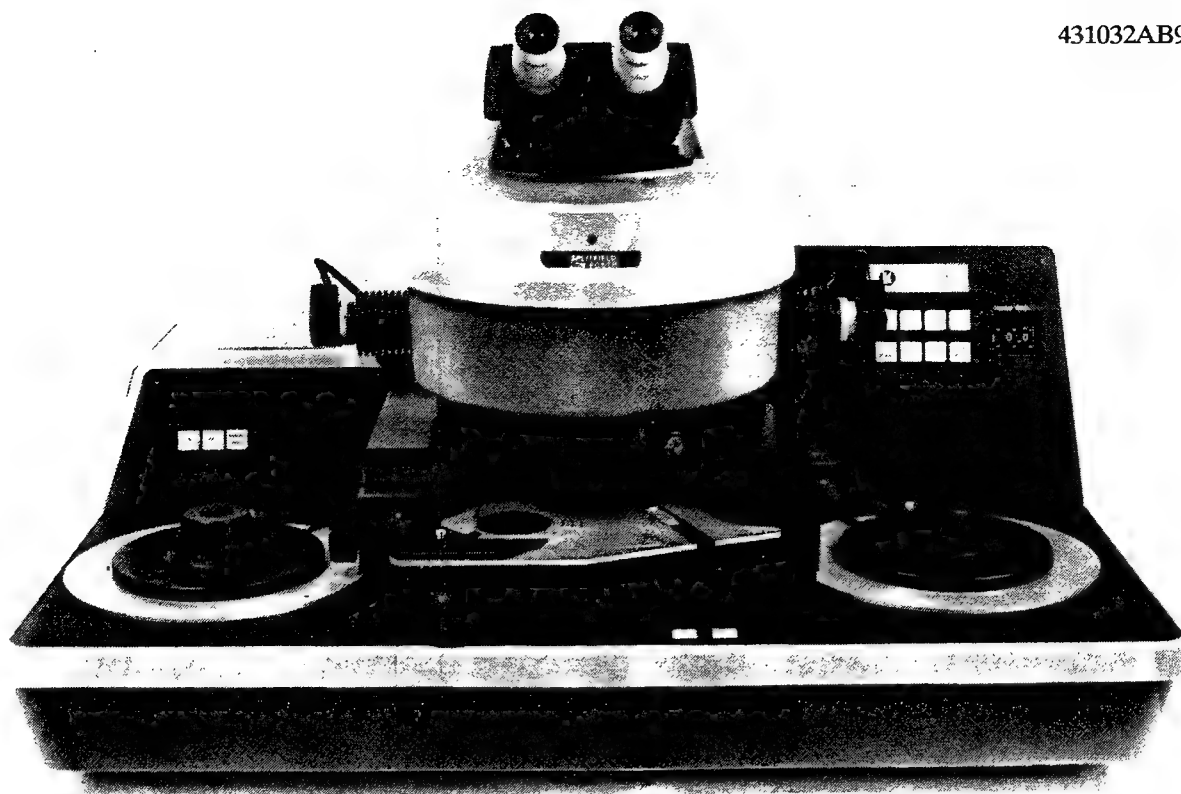
Source: Kasper Instruments
2244-374

Presentation 4.3.1.1.2-1

Kasper's Proximity Aligner
(Circa 1975)

with the hottest new equipment on the market (see Presentation 4.3.1.1.2-3). Needless to say, Perkin-Elmer very shortly came from a position of being totally unknown in the industry to being the number one supplier.

Contact aligners had been selling for a price between $15,000 and $25,000. At the time, scanning projection aligners sold for well over $150,000. This combination of demand and selling price eventually pushed Perkin-Elmer to become the largest supplier of capital equipment in the world.

Still, scanning projection aligners suffer the same loss in resolution as do proximity aligners. The first Perkin-Elmer machine—the Micralign 100 model—had difficulty achieving line widths narrower than about four microns in production. Successive generations of this system, the Micralign 200 and later, the 300, pushed this limit to 2.5 microns. By 1976, the 16K dynamic RAM had already become reality in R&D and was pushing these limits. The 64K DRAMs were being designed at one micron geometries. But poor registration was limiting actual linewidths to two microns.

In the late seventies, most everyone thought the issue was resolution. Thus most researchers believed DUV projection or E-beam would be the winning tool, with steppers being an interim solution. However, the industry hit the one micron barrier in 1980 and backed up to two microns. Perkin-Elmer had overcome the resolution problems by the late seventies. With its DUV Micralign 500, it had resolution capabilities down to 0.9 µm. But total overlay registration remained close to 1.3 µm. This

proved unacceptable for critical layers in production, even at two micron linewidths. Moreover, 1X masks were difficult to build when linewidths were below one micron.

Resolution was no longer the issue, rather it was registration and defect density, in which steppers had the ultimate advantage. At the time, VLSI Research developed the first cost per-good-die model which showed that steppers had the clear economic advantage over other technologies. This economic prowess would soon be proven as those companies that chose steppers would win in their markets, and drive demand for steppers.

Meanwhile, Perkin-Elmer had introduced its Model 500 in the midst of this turbulence under the (then quite rational) assumption that registration and defect density would not be an issue. It bombed in the marketplace. Perkin-Elmer had to go into a costly redesign which would take the better part of two years to recover. Its solutions to these issues were variable magnification, pellicles, and improved mask making meth-

Source: Perkin-Elmer
2244-375

Presentation 4.3.1.1.2-2

The worlds first scanning projection aligner, Perkin-Elmer's Micralign.

Presentation 4.3.1.1.2-3

1976 Wafer Exposure Market
(worldwide sales in $M)

Steppers
0.5

Contact/Proximity
29.7

Projection
31.9

Karl Suss
5.4

Other
4.6

Kasper
6.0

Canon
6.1

Cobilt
6.6

Perkin Elmer
31.9
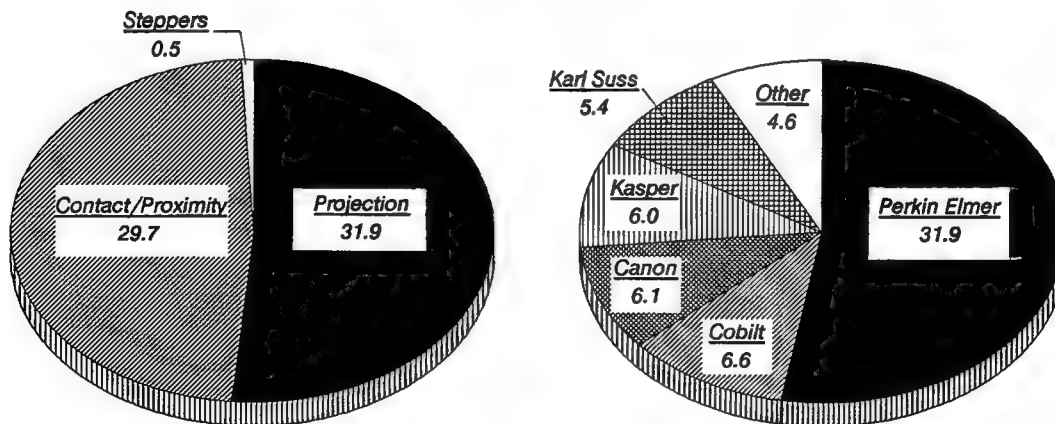
Total Market Size = $61.6M

Source: VLSI RESEARCH INC
2244-376G

VLSI RESEARCH INC

ods. While these were technically effective they were too late to fit into the market timing window.

The first commercial steppers had already been shipped by Kasper instruments in the early seventies. The David W. Mann Division of the GCA Corporation (who had pioneered the development of multiple-aperture step-and-repeat projection systems for reticle making) also recognized that this machine could be converted fairly easily into an aligner (see Presentation 4.3.1.1.2-4).

Steppers offered several new advantages to alignment. As a step-and-repeat system, they were capable of exposing each wafer on a die-by-die basis instead of over the entire wafer. This offered significantly better alignment accuracy (typically 0.5 micron in production at the time). It could also project from a larger image, as much as ten times larger, rather than from the same size projection at a 1:1 ratio. This offered the potential for much higher yield, for defects would be reduced by the reduction ratio. This also eased the burden on mask makers. These early steppers were able to easily produce lines as narrow as 1.25 micron. Substantial performance benefits were soon realized in practice.

But as with projection aligners, steppers were slow to gain acceptance. Kaspers system failed in the market. GCA's first stepping aligner was sold in 1976. But selling prices averaged an astounding one-half million dollars. This was some 30 to 35 times higher than what contact aligners had been selling at only a few years earlier. Nevertheless, these potential benefits proved to be extremely effective. Moreover, stepping aligners outperformed the best yield expectations. Sales thus ballooned rapidly in the early eighties. But in spite of its success, steppers were not considered to be the most technologically advanced aligners until around 1982—seven

years after their introduction (see Presentation 4.3.1.1.2-5). The strength of the projection aligner market, coupled with the emergence of these new automatic stepping aligners caused a major downturn in contact aligner demand in 1978. But emergence of Canon's automatic proximity aligner in 1979 stayed the decline of the contact/proximity aligner marker.

Canon's proximity aligner is shown in Presentation 4.3.1.1.2-6. When Canon introduced its fully automatic proximity aligner, the market was mature and most forecasters were predicting its imminent devise. But, Canon managed to revive the proximity aligner, by significantly raising the productivity of its system and by pricing according
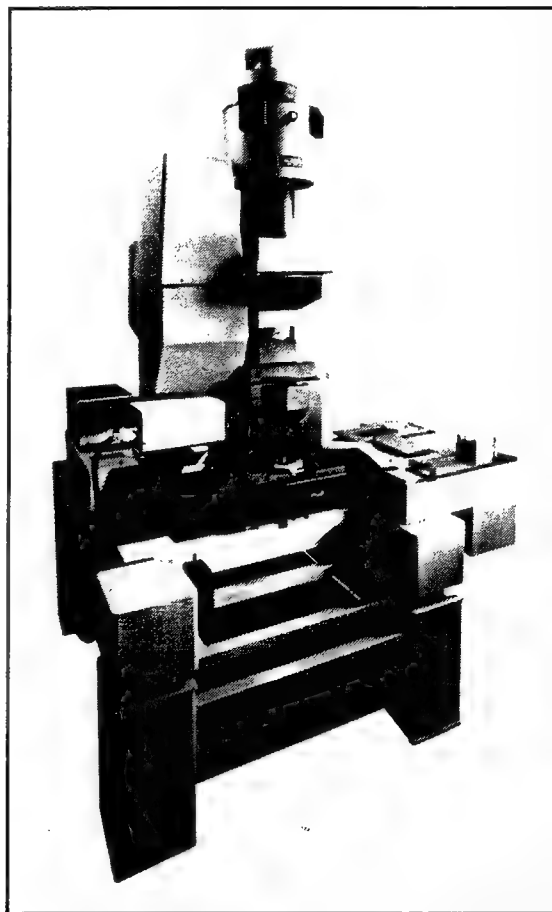
Source: GCA
2244-377

Presentation 4.3.1.1.2-4

GCA's Wafer Stepper

Presentation 4.3.1.1.2-5

Turmoil in the Wafer Exposure Market

Source: VLSI RESEARCH INC
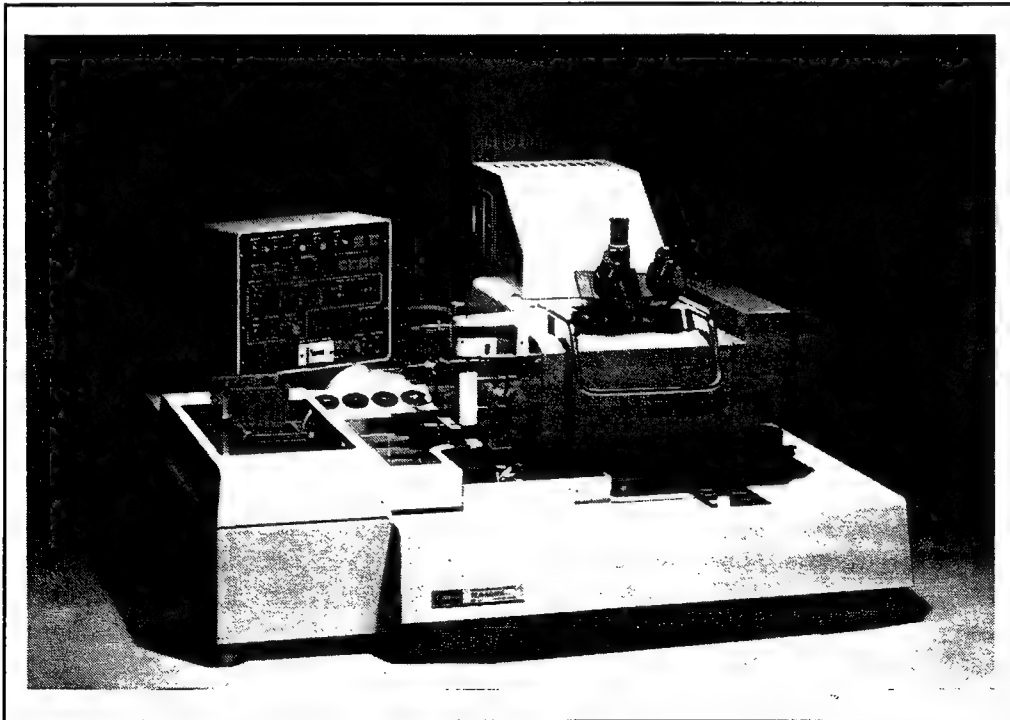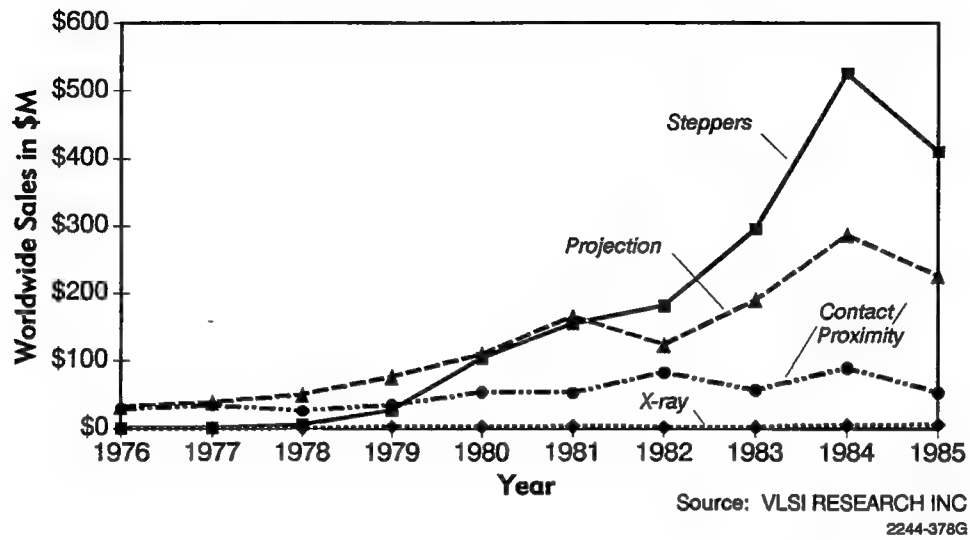
2244-378G

Source: Canon
2244-379

Presentation 4.3.1.1.2-6

Canon's Proximity Mask Aligner

to market value. At the time, selling prices for a manual proximity aligner were around $30,000. Canon's system sold for well over $100,000, but for SSICs with small die sizes, the system was more cost effective than was a projection aligner, and it was half the price. Because of its autoalignment and cassette operation, one operator was able to run three machines at a time, making it extremely cost efficient.

Canon's strategy was a classic for reviving a declining market. They recognized that projection alignment offered significant technical advantages over proximity and that Perkin-Elmer was the key company to compete against. But many customers couldn't use all that capability and Perkin-Elmer's backlog was typically over two years. So they couldn't buy systems in timely fashion even if they wanted to. But rather than try to compete head-to-head with Perkin-Elmer like other proximity aligner suppliers were doing[†], Canon chose a price/performance point that was a midway between scanning projection and manu-

al contact aligners. Consequently, they captured all the customers who wanted to move-up but didn't quite need all the performance of a projection aligner, couldn't justify its cost, or simply couldn't get one fast enough. This strategy was wildly successful & launched Canon on its way becoming one of the leaders.

But, the big story in the 1980s was the stepper. By mid-1980, GCA stepping aligners had become the dominant equipment in use for VLSI manufacturing. Sales were almost as large as those of projection aligners (see Presentation 4.3.1.1.2-7). Soon, steppers would displace projection as the largest segment in lithography. But the battle between the two would not be over for several years.

Because the initial cost of steppers were so prohibitive, users began to look for less expensive approaches. This led to the idea

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† Both Cobilt and Kasper had developed projection aligners by this time.

Presentation 4.3.1.1.2-7

1980 Wafer Exposure Market
(worldwide sales in $M)

X-ray 3.1
Contact/Proximity 53.4
Steppers 103.9
Projection 109.1

Karl Suss 7.6
Eaton 9.5
TRE 15.0
Cobilt 16.4
Other 14.9
Perkin Elmer 99.1
Canon 35.7
GCA 71.3
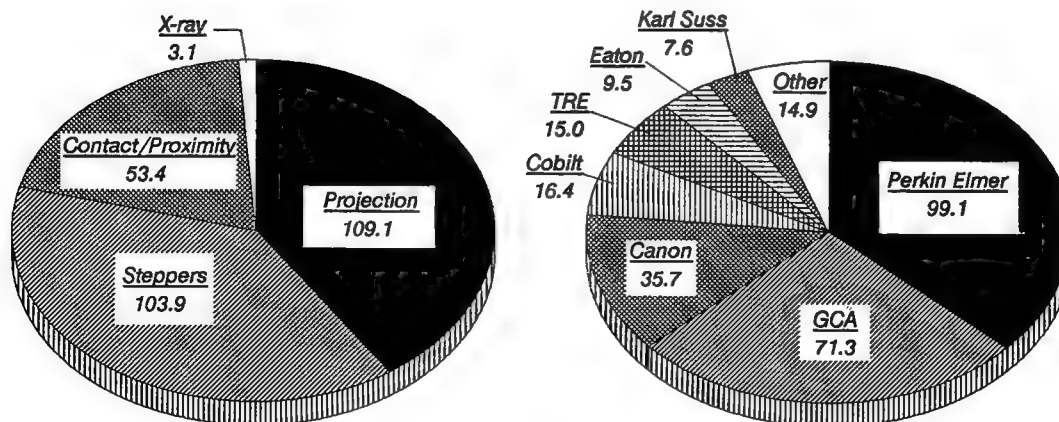
Total Market Size = $269.5M

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of mix-and-match. In mix-and-match, mask layers requiring less resolution are exposed using scanners or proximity aligners, while layers needing greater resolution are exposed with steppers. This created a secondary demand for scanning projection aligners and aided in the rebirth of proximity aligners.

Pellicles caused a big stir in 1982. Apparently, IBM first began using pellicles. Their lead was soon followed by Intel. Following that, Ultratech and Perkin-Elmer were soon pressing hard to encourage the use of pellicles with their equipment as well. Pellicles keep dust particles and other killing defects far enough off the reticle that their image remains out-of-focus. Hence, they do not print in photoresist. At the time, pellicles were found to improve yield by as much as 70%.

Perkin-Elmer's introduction of the model 600, solved the registration problem that had plagued the 500. But it did not ship until 1982. Their failure to recognize the registration issue early-on lead to their missing the market window by three years. By 1982, most semiconductor manufacturer's decisions to switch to stepper had already been made. Too many steppers had been installed for projection aligners to regain a sufficient foothold.

By 1983, steppers had emerged the clear victor over projection aligners. Perkin-Elmer conceded defeat with its purchase of Censor, a European-based stepper manufacturer. In the final analysis, steppers did not win out because projection didn't work. They won out because it was too difficult to make projection work.

With the stepper-versus-projection-aligner debate resolved, several new issues and trends emerged. The question was no longer: 'What type of equipment to buy', but 'Who to buy it from.' Equipment users began looking more for features that would help produce products, rather than for the latest state-of-the-art equipment technology.

Conservative equipment designs which avoided the use of too many unproven innovations began to sell best. Users wanted machines which were simpler to operate. Simplicity in design was also an important feature to users because it made systems more reliable. Simple machine designs allowed in-house maintenance personnel to handle most maintenance and repair. This permitted broken machines to be fixed quickly without having to agonize over the arrival for a repairman.

While GCA was the vendor of choice for steppers, the world was about to witness a switch from American dominance in lithography to Japanese dominance. Nikon would soon become the first successful Japanese vendor to unseat an American leader in wafer fabrication equipment. What followed was an American tragedy, due largely to GCA's arrogance at the time.

In the late seventies, NEC was modifying its GCA steppers to increase reliability and make them more manufacturing-worthy. NEC then asked GCA to produce its modified design.

At the time, GCA was second only to Perkin-Elmer in lithographic technical prowess. GCA's David Mann division was also the world's most innovative company in mask making equipment. They were generally ahead of their customers. Over the years, they had grown accustomed to telling their customers what would work and what would not.

So, GCA told NEC that its modified design would not work and refused to build it. This would prove to be a fatal error on GCA's part. NEC knew the system was an improvement, as they had working systems. NEC, rightly offended, went back to Japan to ask MITI for its help. MITI, in turn,

went to Nikon. MITI actually found it difficult to convince Nikon to enter the market, American companies were extremely strong in lithography, Nikon had only limited exposure to this market through selling its lenses to mask making equipment companies like GCA; more importantly, Nikon was a Mitsubishi group company, whereas NEC was a Sumitomo group company—a rare match. Worse, Sumitomo had a joint venture with GCA to sell steppers in Japan and GCA had been a customer to Nikon for its lenses. But under the pressure of its national importance, Nikon reluctantly agreed to enter the stepper market. Nikon placed its stepper effort in a division entrusted with producing defense products since before World War II.

(Nikon's NSR system is shown in Presentation 4.3.1.1.2-8.)

Stepper sales were about to go into two free falls from which GCA would not recover. The first was in 1982. The second was in 1985. Nikon would emerge as the leader in microlithography by 1984 (see Presentation 4.3.1.1.2-9).

With these events, Nikon was firmly in place and was well on its way to market dominance. The Nikon stepper out-yielded GCA's because its focal plane was flatter, lenses were easier to match between steppers, and Nikon's automatic alignment system was less fussy than GCA's. These factors gave NEC the cost advantage it
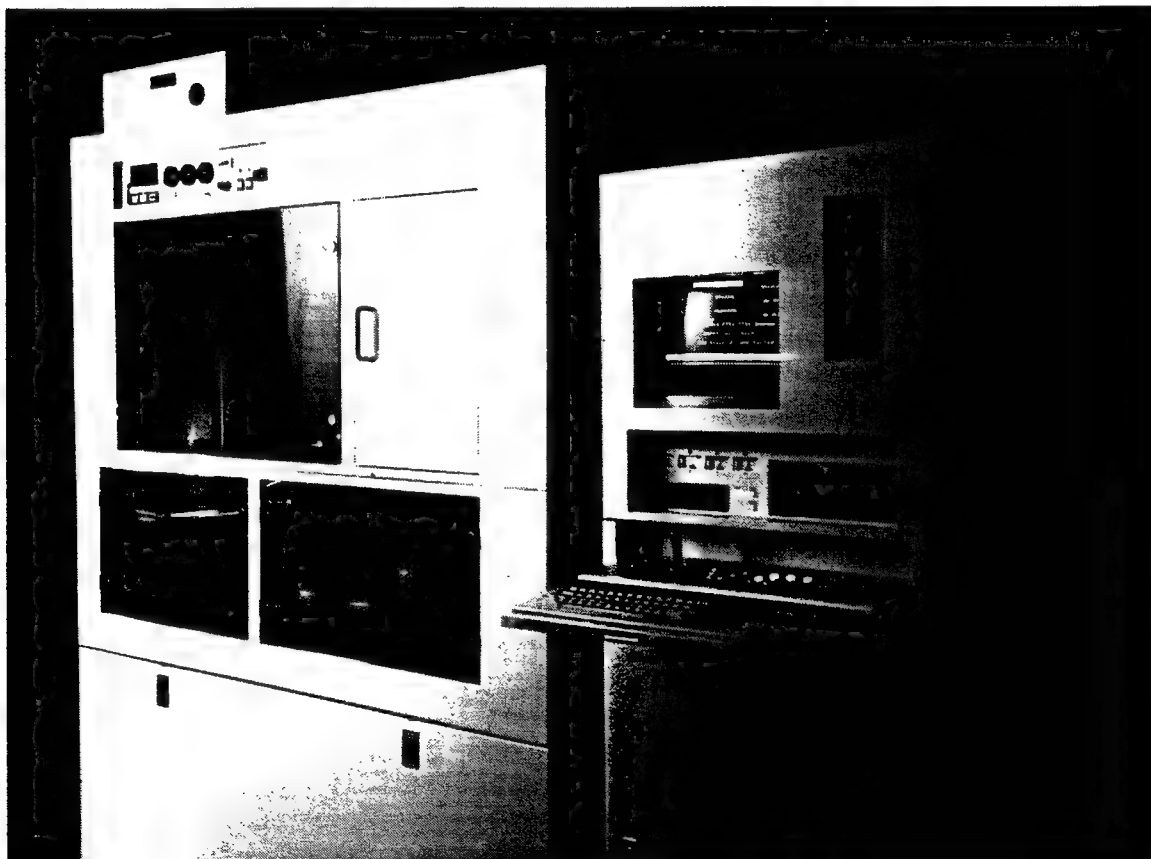
Source: Nikon
2244-381

Presentation 4.3.1.1.2-8

Nikon's Step and Repeat (NSR) Exposure System

Presentation 4.3.1.1.2-9

1984 Wafer Exposure Market
(worldwide sales in $M)

Direct Write 60.4 | X-Ray 5.1 | Contact/Proximity 89.4 | Steppers 525.8 | Projection 286.5

Karl'Suss 24.0 | Hitachi 26.2 | Other 42.5 | Eaton 32.2 | JEOL 38.4 | Ultratech 68.2 | Nikon 187.9 | Canon 175.1 | GCA 186.1 | Perkin Elmer 181.5
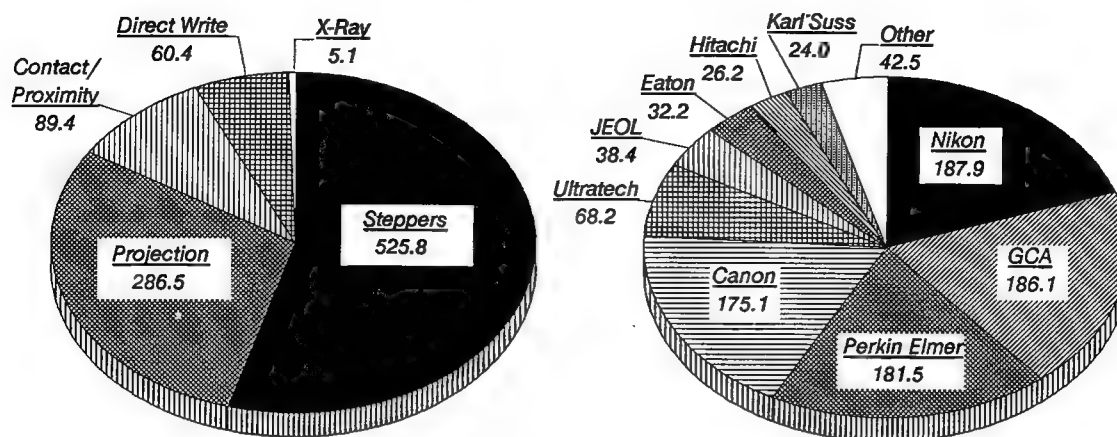
Total Market Size = $962.1M

Source: VLSI RESEARCH INC
2244-382G

needed to capture the 64K DRAM market. They carried Nikon along with them. Nikon first surpassed GCA in 1982. New management and a market up-turn brought GCA back to rival Nikon in 1983 and 1984. But, its fate was doomed.

The late seventies also witnessed a revival in X-ray interest. This was driven by the belief that linewidths would soon fall below 0.8 microns (the perceived limit of optical lithography at the time). Many researchers (including VLSI Research) felt that X-ray lithography would begin to replace the stepper market by the mid-eighties. This was because it was very viable economically, it just could not be made to work at any price. The first attempts at production X-ray aligners were developed in the mid-seventies by AT&T, by the VLSI project in Japan, and by the Massachusetts Institute of Technology. Several companies were entering the market by the early eighties. Micronix Partners, Hampshire Instruments, Nikon and Karl Suss all entered the market in this

period. Micronix Partners was formed out of the old Cobilt X-ray group when Cobilt was acquired by Applied Materials. Their technology was based on AT&T's developments. Nikon had the contract to build Japan's VLSI project system. They were soon selling research tools throughout Japan. Hampshire Instruments was a spin-off from the University of Rochester. Karl Suss efforts were driven by the research efforts of the Fraunhofer Institute to develop Bessy, a synchrotron effort in Berlin.

But, by 1984 it had become evident that production linewidths for optical lithography were being stretched further than anyone had imagined. New photoresists and processing were allowing steppers to stay well head of the market needs. Micronix failed and the others barely survived on government research contracts. The potential of X-ray usage in manufacturing continued to occur as a distraction throughout the eighties, but it was not to come to fruition. To this day, many believe that X-ray is the

Gallium Arsenide of the microlithography business.

While steppers dominated the merchant market, they never really caught on at IBM. IBM was never satisfied with steppers. They had actually built one from a GCA photorepeater in the early seventies. But problems with throughput and lenses led IBM to believe that reflective optics were the best way to go. IBM had made Perkin-Elmer's model 600 work and was the largest user DUV projection aligners, IBM and Perkin-Elmer had always had a close relationship. The foundation of this was based on the friendship built between Tom Wat-

son and Horace McDonnell, who were neighbors. The relationship between these two companies would ultimately lead to the development of the step & scan.

IBM started to work with Perkin-Elmer in the mid-eighties to develop the first scanning stepper. In 1989, Perkin Elmer, introduced the Micrascan (see Presentation 4.3.1.1.2-10). This system was a combination scanner and stepper with a DUV light source. The system offered many technical advantages over conventional steppers.

Like the technologies that came before it, step & scan had a slow start. It was diffi-
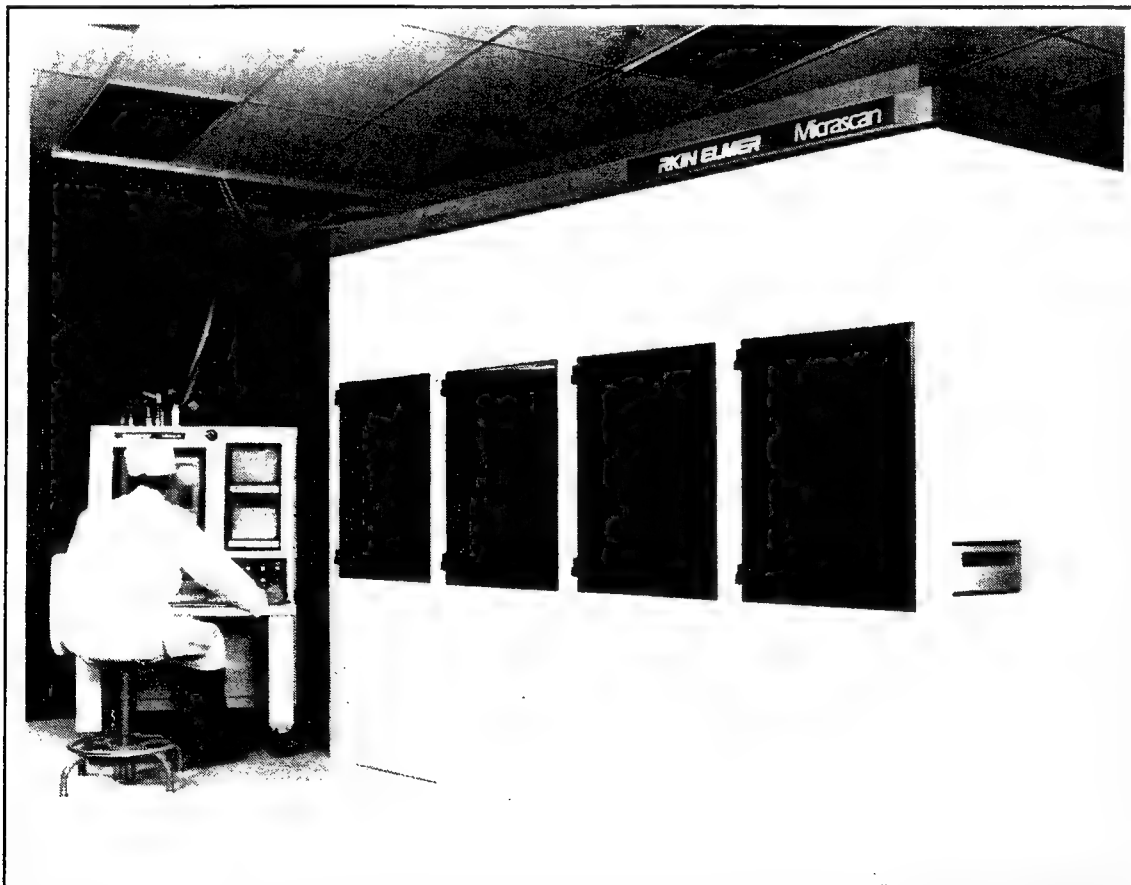
Source: Perkin Elmer
2244-383

Presentation 4.3.1.1.2-10

The Micrascan
(circa 1989)

cult to build. Moreover, it was questionable if any customer other than IBM could afford it, as it sold for $4 million. Perkin-Elmer had also lost the respect of the lithography community. When micrascan was first introduced, SEMATECH declined Perkin-Elmer's invitation to be among the first to view it. Consequently, IBM was the only customer to use it during the first years. Also contributing to the Micrascan's slow commercialization was Perkin-Elmer's divestiture from the semiconductor equipment business. The intent to sell that business was announced in April 1989 and Perkin-Elmer's Optical Lithography Group was acquired by Silicon Valley Group in May of 1990. Today, the Micrascan is regarded as having more potential than any new-generation technology. It may become the biggest breakthrough in lithography technology since GCA's wafer stepper. However, only time will tell.

4.3.1.1.3 Development of the Mask Making Industry

While contact printing was the only wafer exposure method of the sixties, mask making was very advanced. Engineers created rubyliths to make masks by drafting and cutting large drawings of the circuit by hand. Cameras were then used to reduce the drawings to the appropriate size and photorepeaters reproduced the circuit image to make a master mask. The master mask was produced from chrome on glass. Then film emulsion mask copies were made from the master. Film emulsion masks were less expensive. They were also preferred because the contact between mask and wafer caused all masks to wear out quickly. Consequently, semiconductor manufacturers wanted a mask that was inexpensive and disposable.

As in wafer exposure, the seventies was also a hot bed of development in mask making

technologies. Mask making equipment had begun with early step-and-repeat cameras (photorepeaters), but the improvement of the cameras by two key features caused the divergence into mask making and wafer exposure. The second major development of the 1970s was CAD. This led to the market for pattern generators—exposure systems capable of taking the bit patterns from a CAD system and directly patterning a 10:1 reticle. Pattern generators eliminated the need for rubylith. The reticle generated from the 'pattern generator' was subsequently used in a photorepeater to reduce the image and repeat it over the mask.

The original pattern generation tools of the early seventies were optical systems. Meanwhile, AT&T, Texas Instruments and IBM were developing E-beam mask making equipment internally. In 1974, AT&T's Bell Labs introduced an E-beam direct exposure mask making system called MEBES. MEBES was then licensed to ETEC for commercial marketing. ETEC was subsequently acquired by Perkin-Elmer in 1979. Presentation 4.3.1.1.3-1 shows the MEBES exposure system.

The slow speed of E-beam lithography systems spurred continuous development programs designed to produce faster equipment. This led to the introduction by Varian of a new machine, the EBMG-20 (see Presentation 4.3.1.1.3-2). It was followed quickly thereafter with a second version, the Ee-BES-40, offering twice the speed. E-beam equipment began to be used extensively for mask making in 1980. The flexibility of E-beam equipment was a major factor in its acceptance, as mask tooling turn-around-times were reduced to a matter of a few days. Additionally, devices could be easily scaled by reducing the spot size on raster scanning E-beam systems.

However, it was initially thought that these benefits would not be sufficient to allow
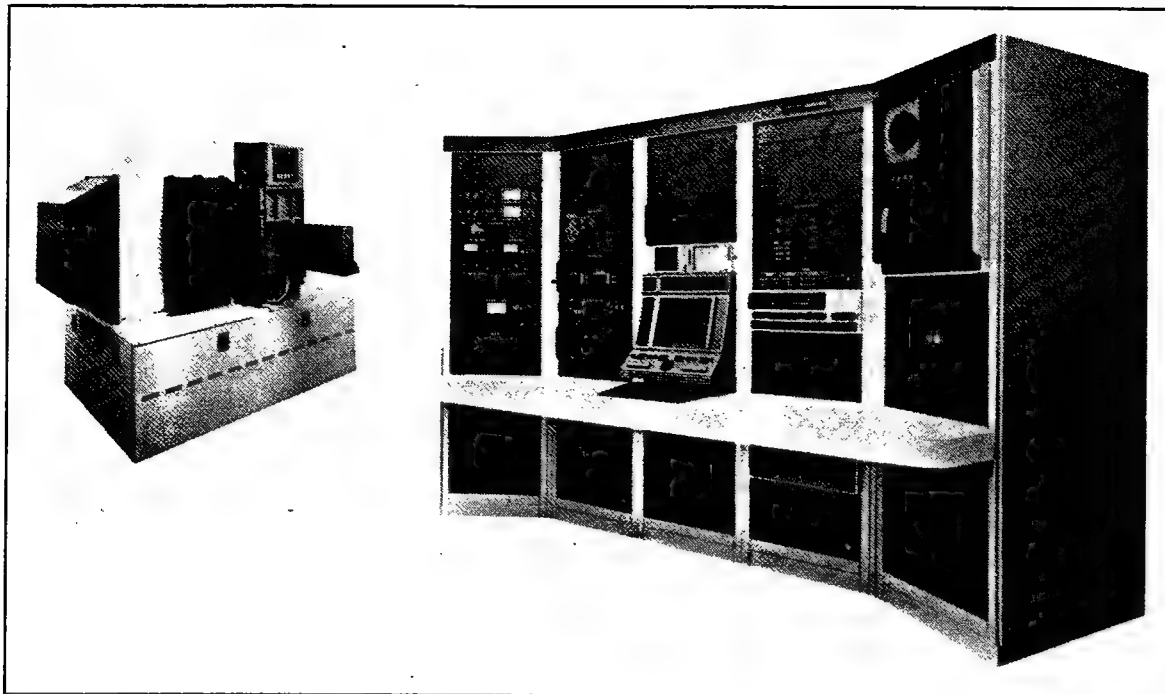
Source: Perkin Elmer
2244-384

Presentation 4.3.1.1.3-1

The MEBES Exposure System
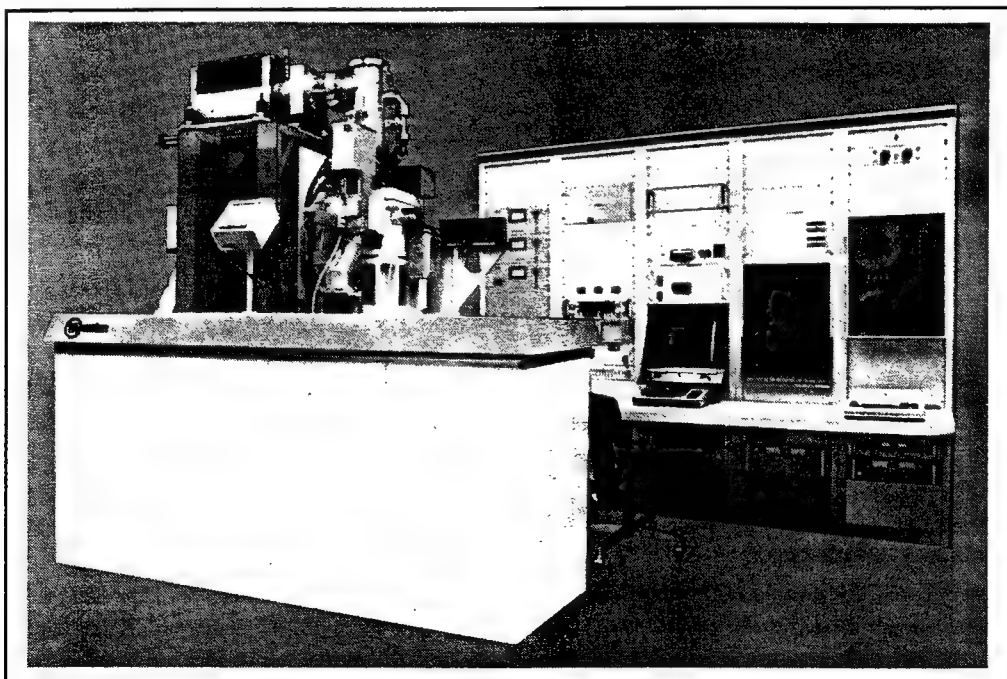
Source: Varian
2244-385

Presentation 4.3.1.1.3-2

Varian's EBMG-20 E-Beam System

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strong market penetration by E-beam masking systems. The high price of an E-beam system was unaffordable to most mask houses. Additionally, E-beam made masks were usually much courser than were optically made ones. Many companies thought this would lead to poorer yields. However, studies showed that E-beam-made masks yielded more die than did optically made ones. One study done at RCA[†] reported that yields increased from 12% to 19% for 200 mil die. The higher yield was attributed to the better registration accuracy of E-beam made masks.

By 1983, the better registration of E-beam made masks had even driven new uses in making masters for proximity aligners. E-beam masks offered solutions to an auto alignment problem which had plagued users of Canon's proximity aligner for several years. This problem had severely hurt the productivity of aligner operators since they had to resort to manual operation. The productivity gain made it economical to use reprints from E-beam masters. Many mask reprints could be made from a master making the amortized cost low. Moreover, it allowed one operator to run three machines. Consequently, E-beam direct exposure soon came to dominate all mask making.

In the early eighties, researchers began to develop laser direct write as a less expensive alternative to E-beam. TRE (later named ASET) was the first to develop a laser beam source for direct patterning as an alternative to the E-beam. TRE's research into laser beam in the seventies never did culminate in a production tool. It used an ultrasonic-deflection that was never successful.

ATEQ was the first company to produce a laser beam mask making tool for production. This system used a rotating mirror deflection system to guide the laser. ATEQ introduced a production machine in 1984 (see Presentation 4.3.1.1.3-3). This machine proved successful because laser beams are inherently more stable than electron beams. ATEQ was able to demonstrate that its system could produce masks with better registration for less capital cost than could an E-beam system.

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† R.A. Gesher, "What Electron-beams can do for LSI," RCA Engineer, Sept/Oct 1980.

4.3.1.2 Technology

Lithographic technology comprises the reproduction of images on flat surfaces. It dates back to the invention of the Gutenberg printing press in 1436. Since that time, the issues have remained largely the same: to obtain finer resolution and more accurate overlay. Lithography technology was successfully transferred from the printing world to the semiconductor world in the early sixties.

Lithography can be broken up into three essential processes: Resist processing, Wafer exposure, and mask making. Resist processing is used to put down a photosensitive layer and then develop it after exposure by an aligner. Wafer exposure is used to print the images from a mask (or reticle) in photoresist on the wafer. These masks are made with mask making equipment.

The technology for each is very sophisticated. Even resist processing has become extremely complex as thickness uniformity requirements have fallen to hundreds of Angstroms across eight inches of silicon.

Engineers must account for the most subtle of variables when designing systems. For example, it is now common to consider the

Presentation 4.3.1.1.3-3

ATEQ's CORE-2000

thermal dissipation off spindle motors in the design of these systems.

4.3.1.2.1 Resist Processing Technology

Resist processing is used in semiconductor manufacturing to deposit photoresist and develop it. Presentation 4.3.1.2.1-1 shows a typical system in production today. This equipment is composed of a series of modules as can be seen by the split covers on the cabinet. This modularity is more clear in Presentation 4.3.1.2.1-2. It shows several resist processing modules interfaced to an aligner to make-up a fully automated lithography island.

The number of modules used on a single track and the complexity of each module tends to increase as linewidths are reduced,

and flexibility needs increase in the fab. Finer resolutions require parameters to be more tightly controlled. This adds more process steps and longer process times. For example, additional chemical treatments and layers are added such as HMDS and contrast enhancement layers. Temperature control and budgeting becomes much more critical at finer geometries. Hot plates and chillers must be added to handle longer times and additional steps. Also, newer lines tend to run many more processes than ever before. This requires more modules to deal with the varying complexity for each process. These relationships are especially true on logic fab lines. It is less true on more efficient memory lines.

Spinners are the core of a resist processing system. They are used for both coat and develop modules. Surrounding this are
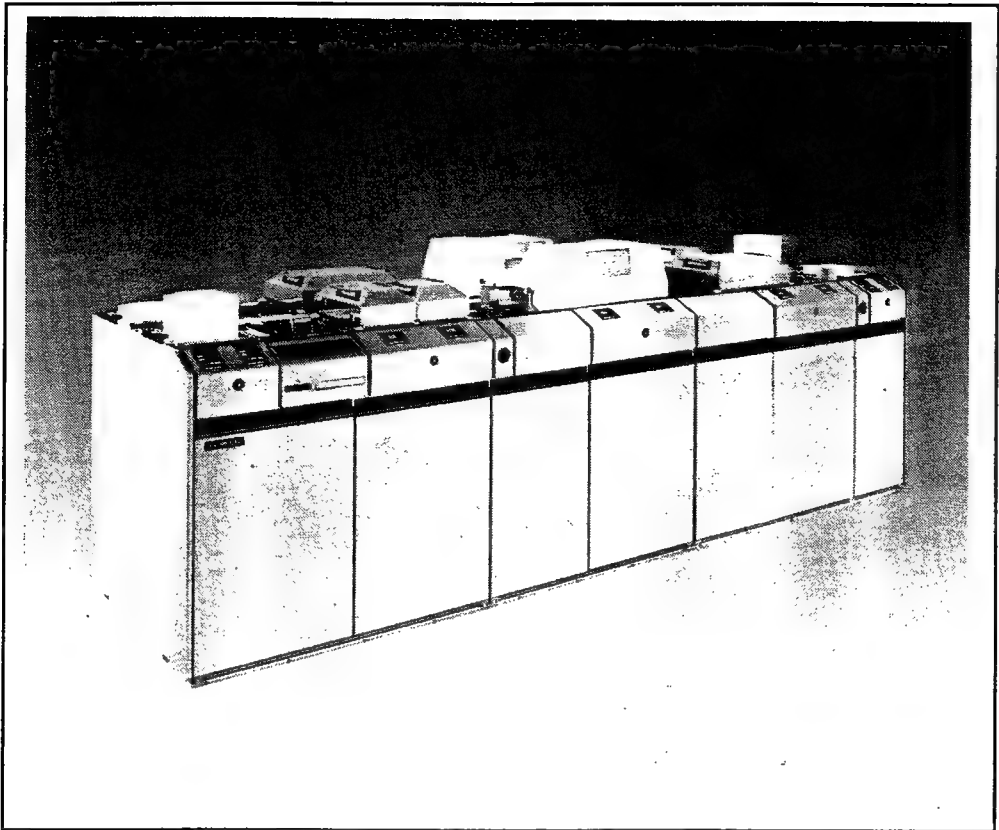
Presentation 4.3.1.2.1-1

Typical Modern Resist Processing System
(Dainippon Screen's D-Spin 629)

SEND	PRIME	CHILL	COAT	BAKE	BUFFER	CHILL & INTERFACE	ALIGNER (NOT TO SCALE)
RECEIVE	BAKE	DEVELOP	CHILL	BAKE	BUFFER		
MASTER							
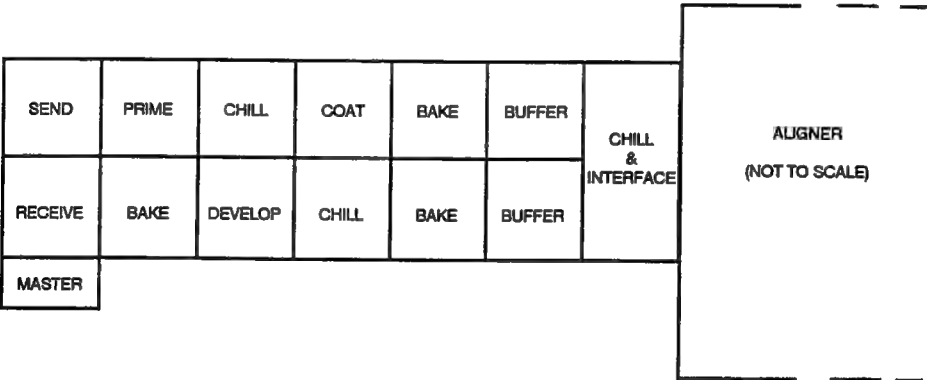
Presentation 4.3.1.2.1-2

Modular Configuration of Resist Processing Equipment

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bake ovens, chillers and vapor prime modules. The mechanics of the process are fairly straight-forward. First, the wafer is vapor primed; then chilled; then resist is poured on and the wafer is spun. The centrifugal force spreads the resist over the wafer's surface, throwing off any excess and creating a uniform coating. Spinning is also used to dry resist. Resist thickness is determined by viscosity, spin speed, surface tension, and drying characteristics. The wafer is then transferred to an oven where it is to a baked soft gel. This is often called a 'soft bake'. The wafer is then chilled again before it is ready for exposure, after which the wafer is chilled, soft baked a second time, chilled again and then returned to spinner for develop. Developer is either poured or sprayed on the wafer and spun. Finally the resist is sent to another oven for a hard bake. This bake hardens the resist so that it can withstand the rigors of etching.

Resist processing equipment must achieve several criteria for successful wafer patterning. Most importantly the resist coating needs to be thin, uniform, planar and defect free. A typical layer is 0.5-1.5 μm thick with a uniformity of ± 0.05 μm over a flat wafer. Planarity over topography is needed to keep the surface of the photoresist within the focus range of the aligner for the succeeding exposure step.

Track systems can be obtained as a whole system or as separate pieces. The equipment pieces include vapor prime, chill, coat, develop and bake. Modern resist processing equipment is arranged in a building block—like configuration. Modules for each different process modules are lined up in a common frame with robotic transfer of wafers between them. Systems are usually custom built to each customer specifications. Frames are custom designed and then modules are placed inside. MTI's Flexifab™ was the first system to use separate frames for each module so that they

could be assembled like building blocks. Each Flexifab module is almost a stand alone system with its own mechanics, electronics and frame. The latest resist processing systems are also enclosed with their own air filtration. The first such system is shown in Presentation 4.3.1.2.1-3.

Vapor priming is used to promote resist adhesion on the wafer. The process envelopes the wafer with hexamethyldisilazane (HMDS) vapors. HMDS traps a molecularly fine film of water at the wafer's surface. For advanced processes, the most common method of applying HMDS is vacuum priming. With it, the wafers are heated in a dry nitrogen atmosphere. After 120-150 °C is obtained, the nitrogen is evacuated, a valve opens and the vacuum pulls HMDS vapors into the chamber.

While spinning may appear simplistic when compared with other film deposition methods, no better method for depositing resist on wafers has ever been found. Designing a spinner to meet today's technical requirements is not trivial. Many seemingly inconsequential factors play a significant role in process results: The thermal dynamics of the motor & chuck must be modeled in order to control uniformity; control of vacuum is essential to avoid chuck pattern imprint in the resist; and control of suckback into the dispense tube is essential to control particulates. All are essential details which must be considered. These systems must also have extensive software control to deal with the many different processes customers use.

Dispensing materials is practically an art form (see Presentation 4.3.1.2.1-4). There is a static application, in which the wafer is held stationary while resist is poured to form a puddle on the wafer, after which chuck is spun. Dynamic application is similar to the static method, but liquids are deposited while the wafer is spinning at low speed, then rotation is accelerated to spread
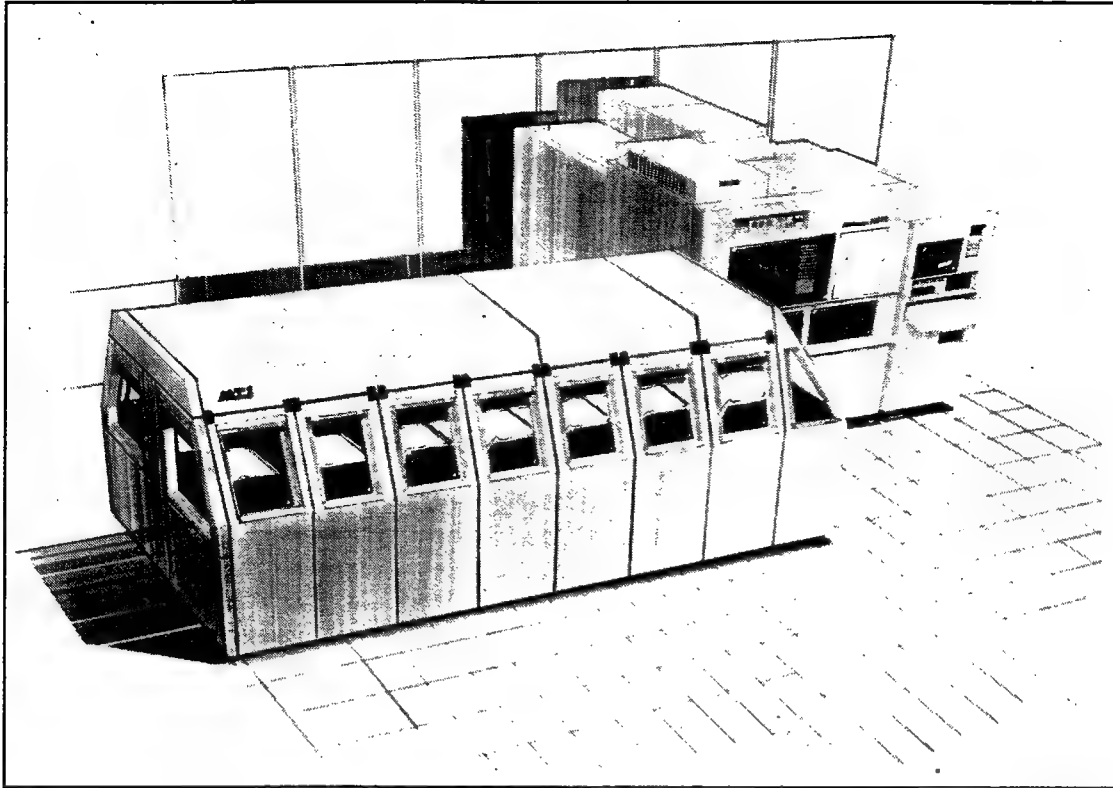
Source: MTI
2244-389

Presentation 4.3.1.2.1-3

Enclosed Resist Processing System

and dry the resist. Another variation is to wave the dispense arm slowly from the center of the wafer to the edge while the wafer spins and liquids are dispensed.

Edge bead removal is another function that the coat module performs. Here, the bead of photoresist that forms around the outer edge of the wafer is removed by spraying a solvent on its backside while the wafer is spinning. This step is essential because otherwise the edge bead will gum up the rest of the track and the aligner with photo-resist. This would then cause a reliability and particulate problem. Edge bead remov-al is probably the most critical step in resist processing. Wrongly performed, it can ruin the photoresist. Spray pressure and spin speed must be accurately designed so that the solvent removes resist on the wafer's backside edge, on its side, and on three to eight millimeters along the top edge without splashing in the top-center. The design of the cup in which the chuck resides is also critical in order to minimize splash-back.

Coat modules are also used in a similar fashion to dispense spin-on-glass (SOG). SOG is used to planarize oxides during latter steps so that the surface of the resist remains in the depth-of-field.

The develop module is essentially the same as a coat module. But, it is used to spin-on developer. Depending on whether the photoresist is positive or negative, exposure to light either breaks up polymer chains or polymerizes the resist. The unpolymerized resist dissolves in developer, leaving a cir-cuit pattern.

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Presentation 4.3.1.2.1-4

Resist Dispensing Methods

Dispense
Arm

Dispense

Spread

Spin

Vacuum
Chuck

No Spin

Slow Spin

High Speed Spin

Static

Dispense

Spin

Slow Spin

High Speed Spin

Dynamic

Dispense with
Moving Arm

Spin

No Spin

High Speed Spin

Moving-arm

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4.3.1 25
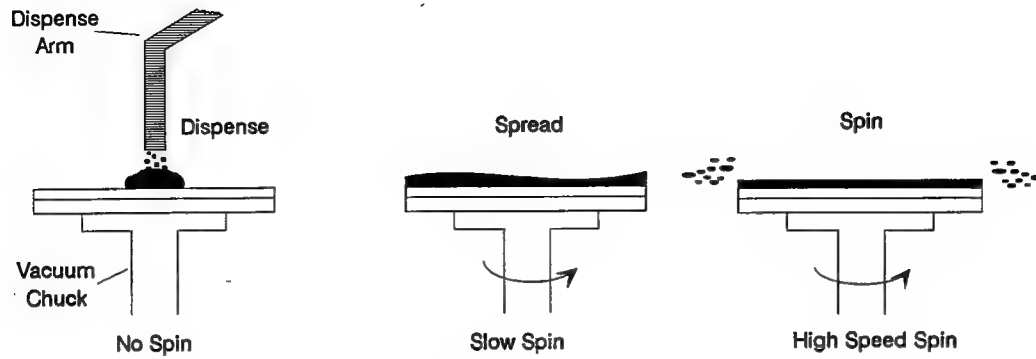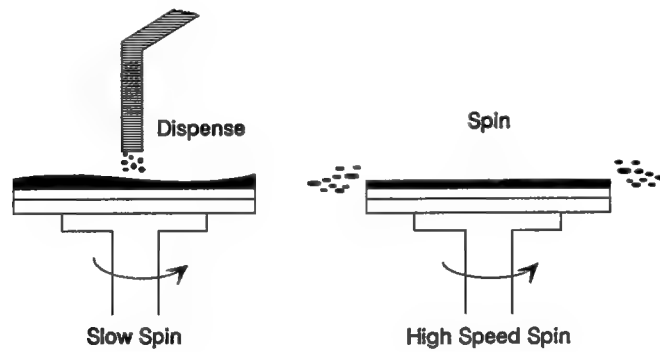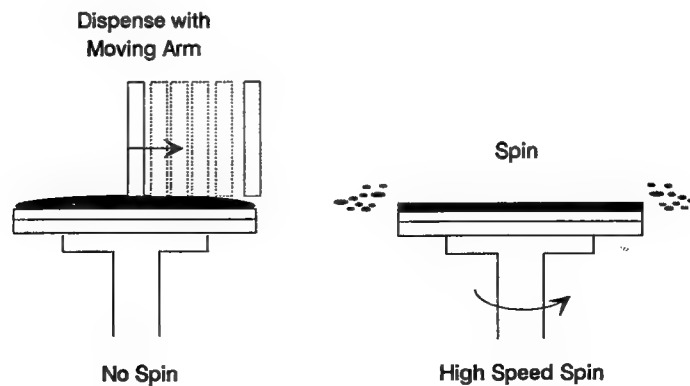
Resist can be developed in a spinner with either a spray process or puddle process. With spray development, a wafer is spun while developer is sprayed on the wafer. With puddle development, the developer is deposited in a puddle on the wafer and left to develop. After a certain time, the wafer is spun and re-sprayed with more developer. After several cycles, it is rinsed and dried. D.I. water is used rinses the wafer and halt development. Ultrasonic nozzles are often used to generate fine mists of developer. This ensures uniform development. One older method of development does not use a spinner at all. Commonly referred to as 'Dip-and-Dunk', wafers are simply immersed in a tank of developer. This is commonly found in use in older fab lines.

The chill plate is used to rapidly cool wafers in order to control thermal budgets and stabilize resist. The chill plate is critical to controlling resist performance, increasing throughput and reducing thermal budget.

The bake module is one of the oldest components in resist processing equipment. The bake module can be used for either soft bake or hard bake. It is essentially a high tech version of a hot plate. Convection ovens and microwave ovens have also been used. However, hot plates offer the best compromise between particulate control and a uniform bake. Most bake modules are single wafer. However, TEL recently started a new trend to multi-wafer hot plates. The primary advantage of this approach is better throughput. Presentation 4.3.1.2.1-5 shows a schematic of a typical bake module. The purpose of a bake module is to evaporate solvents from the photoresist so that the photoresist forms into a soft gel prior to exposure, or into a hard layer prior to etch. Solvents are the largest ingredient, by

VACUUM CAP

HOT PLATE

HEAT SHIELD

VACUUM SEAL

CABLE RETAINER

LINEAR BEARING

LIFTER POST

HEATER PLATE MODULE

HEATER BASE

AIR CYLINDER
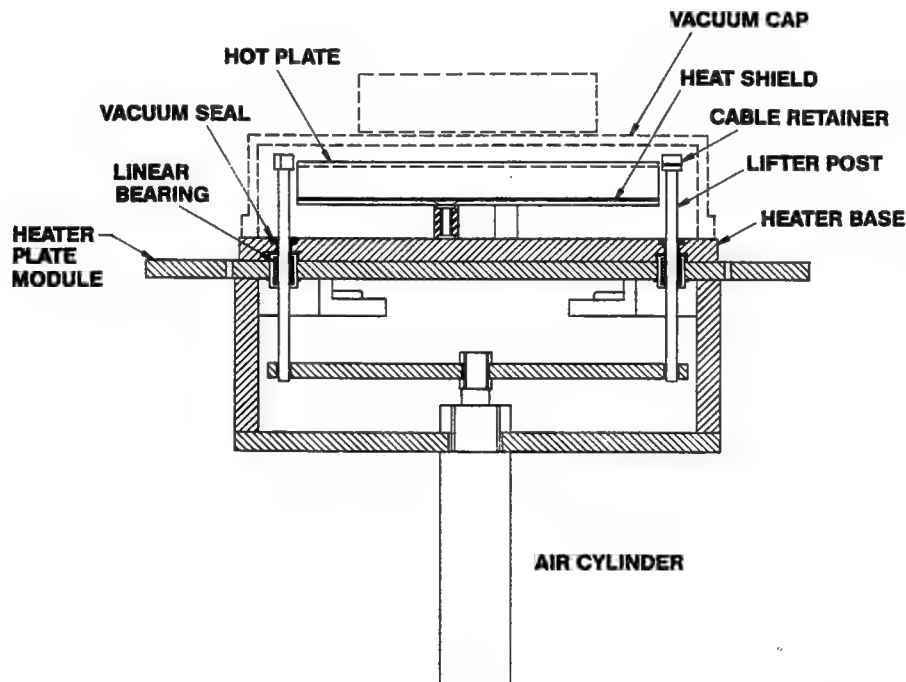
Source: Solitec
2244-392

Presentation 4.3.1.2.1-5

Schematic of Bake Module

VLSI RESEARCH INC

volume, in resist. They are used to adjust the viscosity of the resist. Soft bake is done to evaporate solvents before developing, since they are no longer needed and may interfere with further processing steps. The soft bake is also used for drying, which is necessary for good adhesion prior to resist application. Hard baking is done after developing and just before etching. The hard bake hardens the resist, so that it can withstand etching. It also improves adhesion of resist to wafer, so that it does not lift off in etching.

4.3.1.2.2 Wafer Exposure Technology

The wafer exposure industry has been one of the most technologically active ones in semiconductor manufacturing. It is well recognized that lithography is fundamental to all advances in technology. Finer geometries enable more powerful computers, enabling more powerful software. This, in turn, drives demand for ever finer geometries. This cycle has ultimately lead in some way to most major advances in technology. For example, today's biotechnology advances would not be possible without the advances in computing power that the drive to finer lines has wrought.

The past twenty years have seen dramatic improvements in alignment and exposure techniques. Technological advancement in wafer exposure equipment has evolved across four broad fronts: how the pattern is transferred from mask to wafer, the lens type, the area exposed, and the wavelength of light used. Presentation 4.3.1.2.2-1 lists each of the technologies that fits into these areas. All aligners on the market must use one technology from each of these categories to be a complete system. Equipment designers choose each technology based upon its ability to achieve the resolution needed versus cost tradeoffs.

The method of pattern transfer determines how the image is transferred to the wafer from the mask. The crudest method is to use a contact or proximity method. These are the least expensive methods and can be used when no lens is available (such as the case with X-ray). The disadvantage with either method is that the mask often contacts the wafer, causing damage to both and yield loss. Proximity solves this to some degree. There is less chance for damage to occur when the mask is not in contact with the wafer. The disadvantage with proximity is that shadows distort the image at the outer edges of the wafer. This lowers effec-

Presentation 4.3.1.2.2-1

Essential Aligner Design Choices

Pattern Transfer	Lens Type	Area Exposed	Light Wavelength
Contact/Proximity	No Lens	Whole Wafer	G-Line
Projection	Refractive Optics	Field	I-Line
Scanning Projection	Reflective Optics	Pixel	DUV
Direct Write	Catadioptric Optics		X-ray
	Electron Optics		Electron
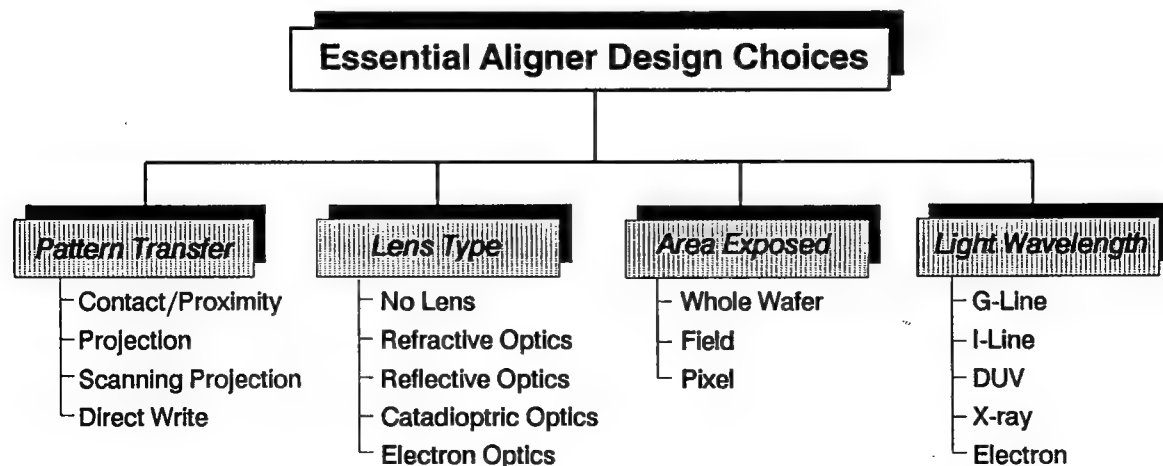
Source: VLSI RESEARCH INC
2244-393D

tive resolution and registration due to run-out error, penumbral blur and diffraction (see Presentation 4.3.1.2.2-2).

Projection eliminates the contact yield problem and it eases shadowing difficulties. But, the first projection aligners were never successful because their use of a point source also caused a shadowing problem across the entire wafer. However, this difficulty was solved with steppers by limit-ing the field of exposure.

These difficulties were also eliminated with scanning projection, where a broad beam of light is scanned across the wafer (see Pre-sentation 4.3.1.2.2-3). Scanning projection allows even more accurate pattern transfer than does projection. However, it is more costly to implement (all things being equal). For example, an SVG micrascan costs roug-hly twice that of a excimer laser stepper. Direct write offers the finest resolution but costs are also high and throughputs are too low to be economical for production.

Lenses for aligners vary significantly in complexity. The simplest exposure systems use no lens at all. More complicated sys-tems use arrangements of lenses, mirrors, or both. Refractive optics project the image of a mask onto a wafer through lenses. Pre-sentation 4.3.1.2.2-4 shows a simplified example of refractive optics. Actual stepper lenses can have 20 elements or more. They can be almost three feet in length and weigh in excess of 500 pounds.

Reflective optics use mirrors to reflect the image and expose the wafer (see Presenta-tion 4.3.1.2.2-3). Manufacturers prefer catadioptric lenses for more complex prob-lems because they do not restrict the field. A catadioptric lensing system uses a combi-nation of refractive and reflective optics in wafer exposure, as shown in Presentation 4.3.1.2.2-5.

The area of the wafer exposed is also a significant indicator of technology. Smaller areas of exposure offer more control. Larger areas offer greater throughput. Contact, proximity, and projection aligners expose the entire wafer at a time. Steppers expose only a field at a time, taking many exposure steps to pattern the entire wafer. Direct write exposes only one pixel at a time. With direct write, there are typically four spots per line. So it takes 16 spots to expose any square area, making this method the slowest.

Light wavelength is one of the most impor-tant parameters determining the capability of an aligner. Optical exposure techniques use g-line (436 nm), i-line (365 nm), or DUV (248 nm) light. X-ray sources offer

Presentation 4.3.1.2.2-2

Shadowing Problems with Proximity Printing
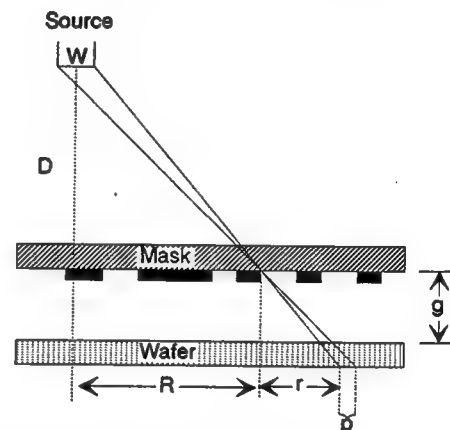
r : Run out error $= (g/D)R$

p : Penumbral blur $= (g/D)W$

d : Diffraction blur $= \sqrt{g\lambda/2}$

Where: λ = Light wavelength

g = Gap between mask and wafer

D = Distance from source to wafer

R = Length across wafer from source centerline to feature edge

W = Width of source

wavelengths below 0.8-2.5 nm. Shorter wavelengths offer better resolution and depth of focus. However, shorter wavelengths are achieved at a cost: Illuminators produce less light and optical materials (glasses) are more absorbent, and so throughput suffers. Additionally, lenses are more difficult to build when shorter wavelengths are used. There are fewer glasses that will transmit light at shorter wavelengths. This is important to lens designers because they use mixtures of optical materials to correct for aberrations such as astigmatism, coma, spherical, and others. But at DUV wavelengths, fused silica (S_iO_2) is the only glass that transmits light without absorption. There are other materials, but these are difficult to work with, which will be elaborated on later in the text.
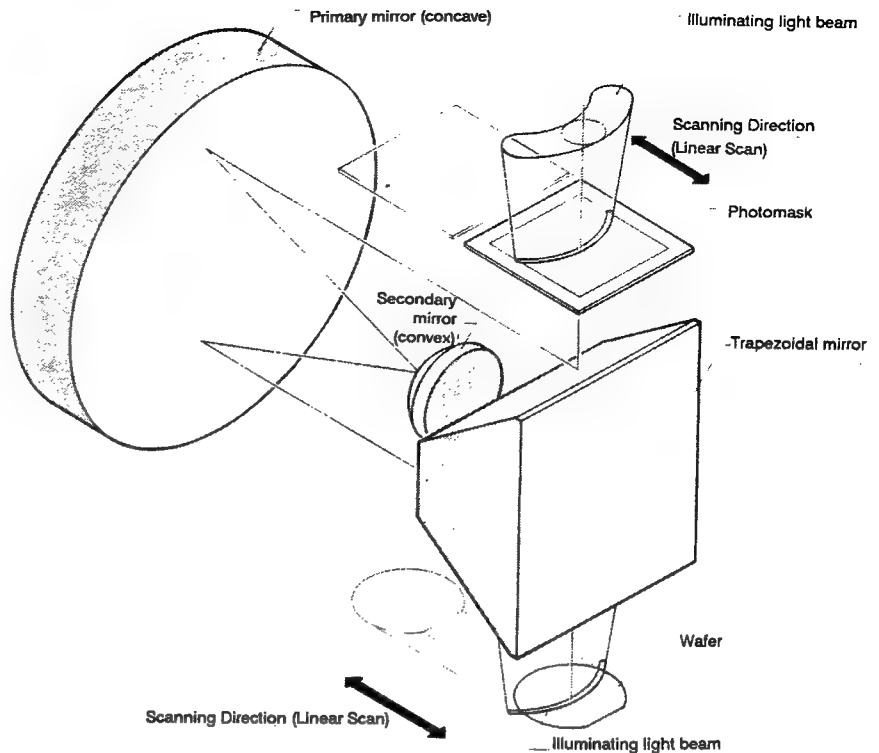
Presentation 4.3.1.2.2-3

Scanning Projection

Lens designers are able to avoid shorter wavelengths by using higher numerical apertures (N.A.). A higher numerical aperture produces better resolution. But it decreases depth of focus, thereby decreasing process latitude[†]. Eventually, depth of focus limitations force a shift to shorter wavelengths.

[†] The effects of wavelength and numerical aperture on resolution and depth of focus are well documented. The resolving power of a lens, known as the Rayleigh limit, determines the theoretical linewidth that is achievable.

$$l^{th}_{\omega} = \frac{k_1 (\lambda)}{NA} \qquad 1)$$

$$DOF = \frac{k_2(\lambda)}{NA^2} \qquad 2)$$

Where λ is the radiating source wavelength, N.A. is the numerical aperture; and l^{th}_{ω} is the theoretical linewidth. k_1 and k_2 are constants relating to light coherence, and are generally found to be 0.7 and 0.5 respectively, in production environments. Linewidth decreases when N.A. is increased. However, depth of focus decreases much more rapidly since N.A. is squared.
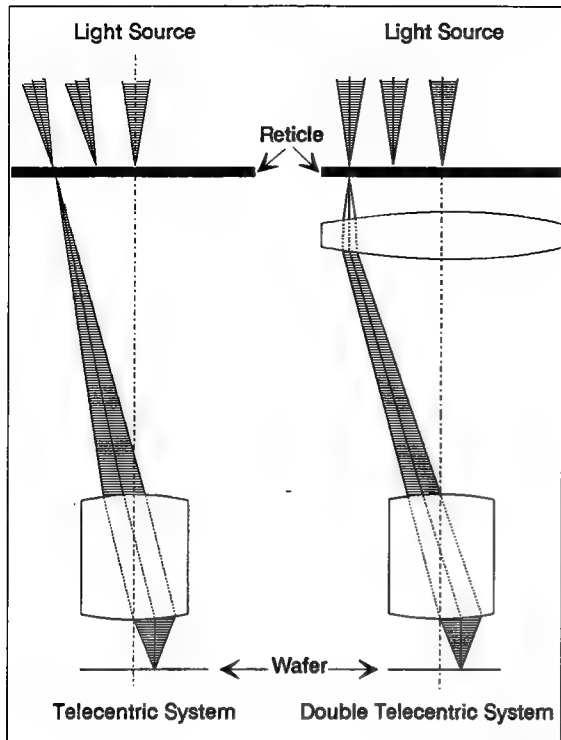
Source: Canon
2244-395D

Presentation 4.3.1.2.2-4

Refractive Optics for Stepping Projection

Presentation 4.3.1.2.2-6 shows how each type of aligner in use today for advanced IC manufacture utilizes the technologies discussed above. It can be clearly seen from this example that the technologies are broken-up into multi-dimensioned levels of capabilities. This often makes for confusion among individuals new to the industry. Typical questions asked are:

- Why is there continued research into X-ray when it is based on proximity alignment, an old technology?

  While there are no lenses available for X-ray steppers, its extremely short wavelengths offer the potential of much better resolution and depth of focus. The large depth of

focus and the use of field exposure eliminates many of the yield problems associated with the proximity method.

- If E-beam offers the most advanced solution available, why isn't its market larger?

  Because the serial method of exposing each pixel at a time is too slow to economically justify its use for high volume production.

These questions are covered in more depth in the following portion of this section.

Available Alignment Equipment

There are four types of alignment equipment in use today. They are proximity aligners, steppers, X-ray aligners, and direct exposure. Each of these and their variants are described here.

Proximity aligners are the oldest type of system in use today. They are often referred to synonymously with their older antecedent, the contact aligner. This is because they are essentially the same technology. The key difference is that with proximity, the mask is not in 'hard' contact with the wafer, but is in close 'proximity' to the wafer surface. Control of this gap is essential to obtaining good results with proximity alignment. The gap must be maintained within ±3 μm to achieve a repeatable linewidth quality. Larger gap errors reduce resolution. Presentation 4.3.1.2.2-7 shows Canon's method of setting the proximity gap. Since this gap is typically 20 microns, and wafers vary by several mils (25.4 microns). The mask is actually in contact with the wafer. But, the amount of contact is far less than the old contact aligners that mechanically clamped the mask onto the wafer and sucked it down with a vacuum.

Presentation 4.3.1.2.2-5

Catadioptric Lens Design
(Wynne Dyson)

Reticle

Wafer

Source: Ultratech Stepper
2244-396D
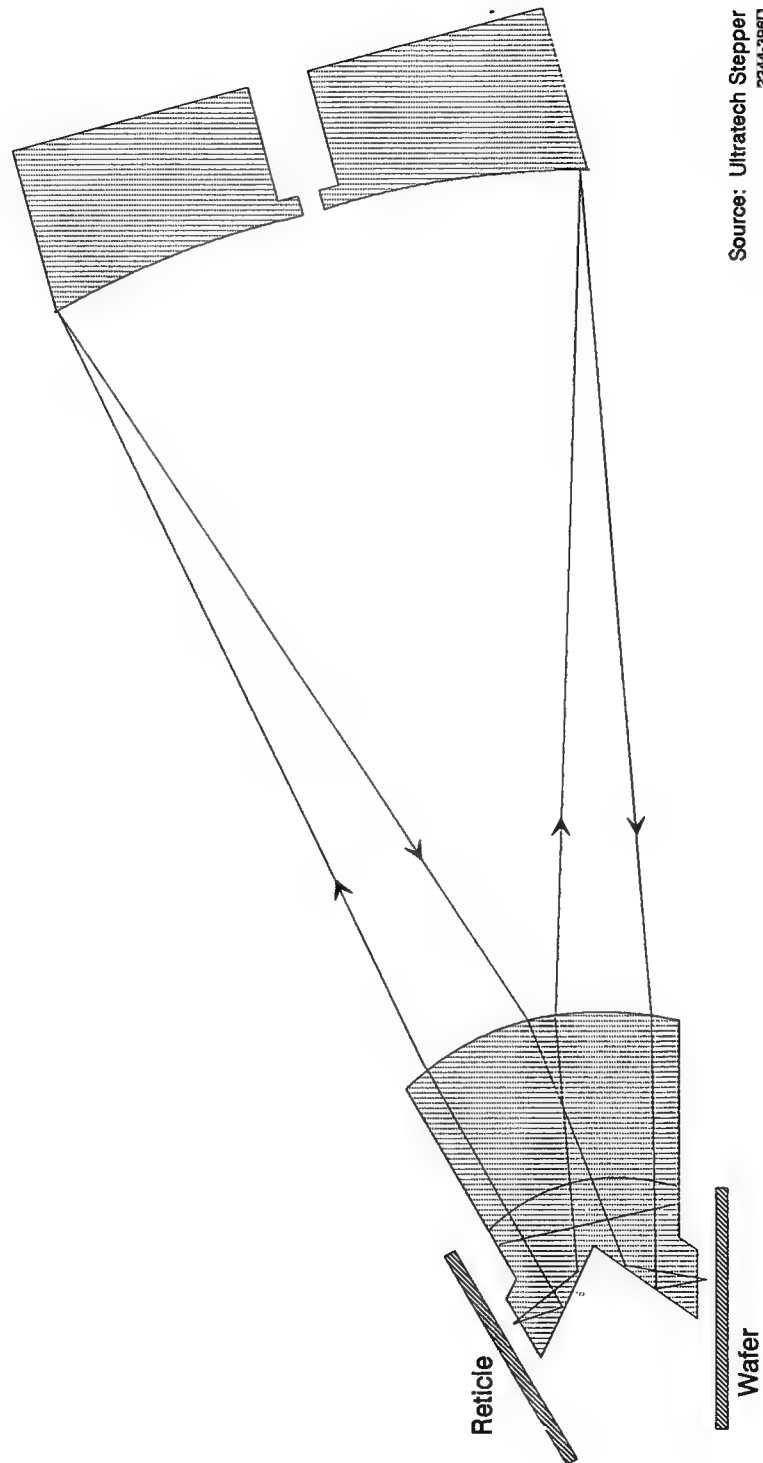
Technologies used by Wafer Exposure Equipment

Technical Characteristic	TECHNOLOGY				
	I-Line Stepper	Excimer Laser Stepper	Step & Scan	X-Ray Stepper	E-Beam
Pattern Transfer	Projection	Projection	Scanning Projection	Proximity	Direct Write
Lens Type	Refractive	Reflective	Catadioptric	None	Electron
Area Exposed	Field	Field	Field	Field	Pixel
Light Wavelength	I-Line	DUV	DUV	X-Ray	Electron

Source: VLSI RESEARCH INC
2244-398D

Proximity aligners typically expose a whole wafer using DUV wavelengths. However, there is significant variation in wavelengths used. This is because larger wavelength lamps put out more energy. This improves throughput. Additionally, some DUV proximity aligners are configured as manual steppers for R&D purposes. These systems provide very low cost sub-micron exposure tools.

Resolution to very small geometries is achievable with proximity aligners. However, whole wafer versions lack the registration needed for linewidths below three or four microns. Moreover, the main problem with proximity aligners stems from the very nature of the system itself. Because the mask still comes in direct contact with the wafer, short mask lifetimes and particulate contamination continue to be serious problems. This contact scratches masks, thereby making it necessary to replace them often. This is an added expense not found with other types of exposure systems. The contact also causes resist to lift off the wafer and attach to the mask, which creates de-fects. Overall, these detrimental effects lead to significant yield deficits with proximity printing.

These effects can be lessened by increasing the gap. But increasing the proximity gap also decreases resolution. Diffraction and penumbral blur are the primary issues here.

Distortions due to run-out error are no longer a serious problem for proximity aligners. This is because illuminators are designed to broadly focus light on the mask. Presentation 4.3.1.2.2-8 shows how a modern illuminator projects light on the back of a mask to provide uniform exposure across a wafer.

Scanning projection aligners represent a significant advancement over proximity aligners. Yield is higher because there is no contact between mask and wafer. Linewidths are also smaller because of the use of sophisticated lenses. In scanning projection exposure, an arrangement of concave and convex mirrors is used to make up a reflective optics assembly (see Presentation 4.3.1

1st step: Wafer loading

① A + B + α (4th step)

(Lower wafer chuck to load wafer)

Parts	④ Wafer
① Photomask	⑤ Wafer chuck
② Photomask holder plate	⑥ Unit 1
③ Calibrator	⑦ Unit 2

2nd step: Calibrator inserting

B   A

(Insert calibrator)

3rd step: Equalizing

A + B

(Equalize wafer)

4th step: Initial gap setting

A + B + α

α

(Lower wafer from calibrator by some interval)

5th step: Preparing for calibrator removal

A + B + α + β

β

(Ready to remove calibrator)

6th step: Final gap setting

Ga

$A + B + \alpha + \beta - Ga$

A + B

Ga ..... Alignment gap

(Calibrator removed and alignment gap between mask and wafer made)

ce: Canon
2244-399

Presentation 4.3.1.2.2-7

Proximity Gap Setting Method

.2.2-3). Light is scanned through a slit onto a mask and its image is projected onto a wafer. The light field is moved simultaneously across mask and wafer. In this way, the image is reflected off mirrors and reproduced accurately on the wafer's surface. The system uses no reduction (the transfer ratio is 1:1) and the entire wafer is exposed one pass.

Scanning projection technology offers excellent production resolutions in the 2 to 4 micron range, with adequate registration. Because it scans the whole wafer at a time it achieves much higher throughputs than does a stepper. This makes it an excellent choice for ICs with LSI scale integration levels, TFT displays and multichip modules.

① Super-high-pressure mercury lamp
② Ellipsoidal concave mirror
③ First mirror
④ Collimator
⑤ ND filter
⑥ L-39 filter
⑦ Fly's eye lens
⑧ UC filter
⑨ Second mirror
⑩ Condenser lens
⑪ Detector
⑫ Condenser lens
⑬ Mask plane
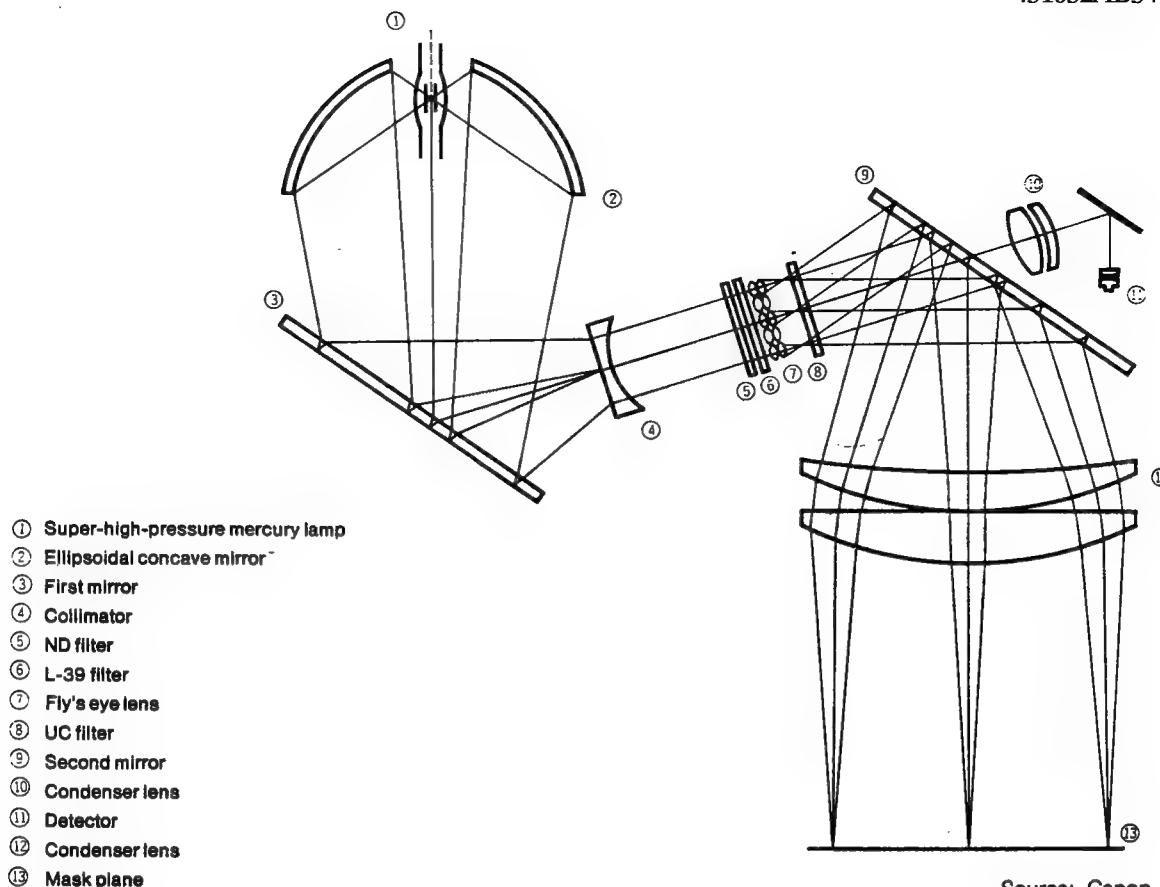
Source: Canon
2244-400

Presentation 4.3.1.2.2-8

Optical Layout of Canon's Proximity Illuminator

Its major weakness is registration. The best projection aligners typically achieve 0.5 micron registration in a production environment. This limits production resolution to 2.0 microns when a 4X error budget is used. Another limiting factor is that 1:1 masks are difficult to make and expensive for linewidths below two microns. Additionally, they are difficult to use when long exposure times are needed because they must scan the entire area. Long exposure times are essential in making thin film heads. Consequently, projection aligners are in limited use today.

Steppers are the workhorses of modern day microlithography. They evolved out of the need for significant improvements in overlay accuracy over whole wafer exposure methods. Steppers have inherently better regis-

tration due to their ability to align to a predetermined point with each step. This eliminates optical distortions in alignment due to whole wafer exposure.

Since the field size is smaller than in full wafer exposure, the step-and-repeat method also improves focus and has less distortion. Both of which serve to give a deeper virtual depth of focus.

The stepper is generally considered to offer the best combination of leading technology and cost effectiveness. Every successful new alignment technology introduced since the late seventies has used a stepper platform. The primary thrusts in new technology development have been the use of shorter wavelength illuminators or catadioptric lenses.

Reduction steppers with refractive projection optics and g-line sources were the most commonly used among systems of the eighties. The g-line wavelength is 436 nm. This limits its production resolution to about 0.8 microns. Presentation 4.3.1.2.2-9 shows a typical optical assembly for a stepper. Steppers with **i-line sources** (365 nm) offer resolutions that can be extended to 0.5 micron in production and to 0.35 micron with phase-shift masks. Several companies are already using i-line technology for 64M DRAM development, increased numerical apertures and field sizes will likely extend its life through the mid-1990s.

Deep-ultraviolet light (DUV) steppers are at the cutting edge of microlithography. There are three types of DUV steppers: Excimer laser, Step & Scan, and Markle-Dyson. Their wavelengths vary between 200 and 300 nanometers. Excimer laser steppers have been the most popular because they are technically similar to conventional g-line or i-line steppers. The only difference is their use of a excimer laser illuminator. Such a system is relatively simple to develop in contrast to the other contending systems. Consequently, most suppliers of conventional steppers also offer an excimer laser version. Excimer lasers offer several usable wavelengths of light 306 nm, 248 nm, and 193 nm. Presentation 4.3.1.2.2-10 show the resolutions that each can achieve. The most common wavelength used is 248 nm, which is produced by a krypton fluoride source.

The key advantage of using a laser is in its greater output of light. This is necessary because excimer laser steppers use refractive optics. Consequently, they need high powered illuminators because glass tends to absorb shorter wavelengths of light. However, there are many technical issues with **excimer laser** steppers. Excimer lasers have high maintenance costs. This is because the high power of the laser causes photoresist and air particles to photo dissociate and

Presentation 4.3.1.2.2-9
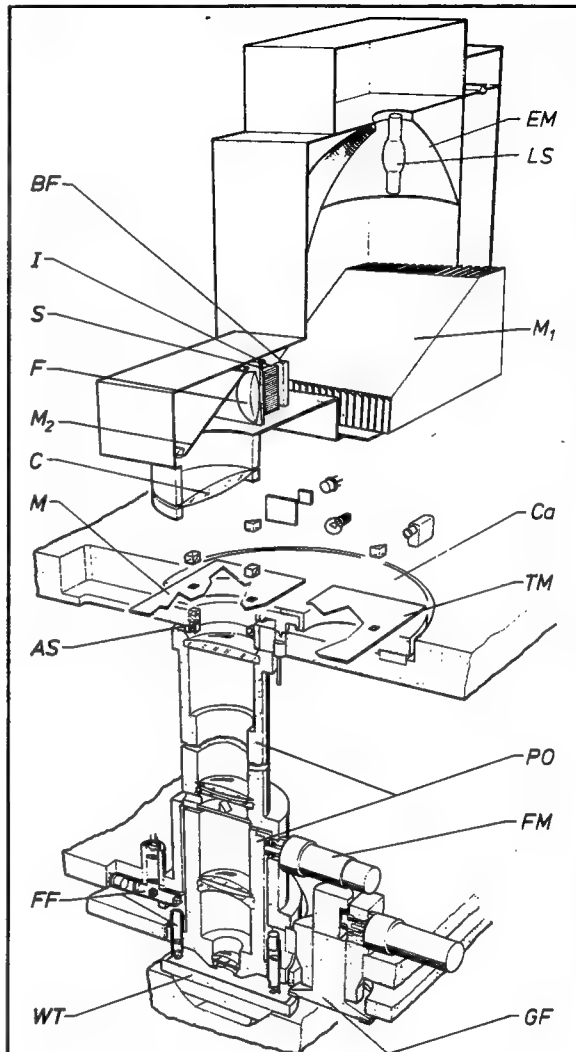
Conventional Stepper Optics

Fig. 2. Drawing of the optical system. *LS* high-pressure mercury-vapour lamp, 350 W. *EM* elliptical reflector, M_1 and M_2 flat reflectors. (M_1 is at the same time a multilayer interference filter that only reflects radiation at wavelengths below 450 nm.) *BF* bandpass filter (also a multilayer interference filter), which passes radiation of 395 to 440 nm. *S* shutter, necessary because the mercury-vapour lamp is not switched off between the projections. *F* field lens. *C* condenser. *I* optical integrator, whose operation is explained in fig. 3. *Ca* carousel for two masks; masks can be changed in 1.5 s. *M* mask. *TM* mask for test patterns. *AS* optics of alignment system. *PO* projection optics consisting of two parts. *FM* motor for displacing the lower part of *PO* for fine focusing. *FF* optical system for fine focusing. *WT* wafer table. *GF* mechanism for adjusting the upper surface of the wafer to a predetermined height (coarse focusing) and perpendicular to the optical axis. (In *WT* the spherical bearing for the angular displacement is shown but not the bearing for the vertical adjustment.)

Source: ASM Lithography
2244-401
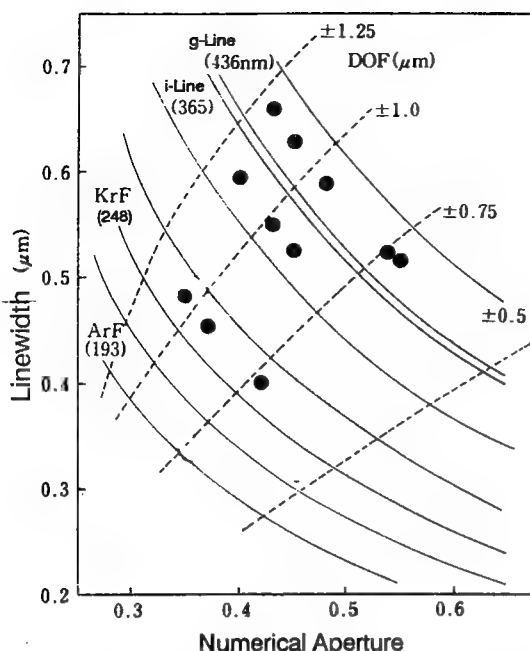
Source: NEC via Semiconductor World June '90

2244-402

Presentation 4.3.1.2.2-10

Improved Capabilities of DUV Steppers
(248NM & below)

deposit on the lens, thus requiring lots of cleaning. More importantly, the laser causes radiation damage to lenses (both in the lens assembly and in the laser itself). The gases used in an excimer laser tend to corrode its lenses. These problems can be resolved by using lenses made of MgF_2 and CaF_2. But, these materials are expensive, and difficult to work with. These are also issues for the stepper lens itself. Radiation damage to lenses has been a significant problem limiting acceptance of excimer laser steppers. The intensity of the laser causes fluorescence and color-formation defects in lenses. Fluorescence results in non-uniformities in exposure. Color-formation reduces light transmission through the lens. This because the laser induces defects in the crystal lattice of the lens. These cause color centers where certain wavelengths of light are filtered out, creating a

discoloration in the lenses. This problem is aggravated with fused silica glass because it is in a "super-cooled" liquid state. Molecules are moved closer together whenever they are hit by two or more photons at a time. Consequently, the glass gets denser. So it shrinks, causing the index of refraction to go up, which creates aberrations across the lens. This is a major problem since stepper lens uniformity must be held to a precision of a twentieth of wavelength (12.4 nm for a 248 nm lens). These difficulties increase with repeated exposure until the lens must be replaced at a cost exceeding $500K. Even lens elements made of CaF_2 are susceptible to radiation damage. Stepper lenses cannot be made with MgF_2 because it is birefringent. It can only be used for windows.

The design of the excimer laser is extremely critical since radiation damage is roughly proportional to the square of the instantaneous energy of the laser. Thus:

$$Rd \sim K \cdot I_I^2$$

Where: I_I = Instantaneous Energy
K = Constant
Rd = Radiation Damage

Longer laser pulses significantly reduce damage. Pulse length can be doubled or tripled without affecting throughput, since pulses are typically measured in tens of feet.

Step-and-scan steppers avoid these problems altogether by using a conventional mercury arc lamp source in place of an excimer laser. This is possible because they mostly use reflective lens elements. This also gives it a field size that is over twice as large as a conventional stepper. Step-and-scan technology also offers the optical advantages of scanning along with the registration advantages of stepping. Presentation 4.3.1.2.2-11 shows the step-and-scan principle. It scans the field instead of using a flash exposure. This gives it technological advantage in its ability to perform on-the-fly
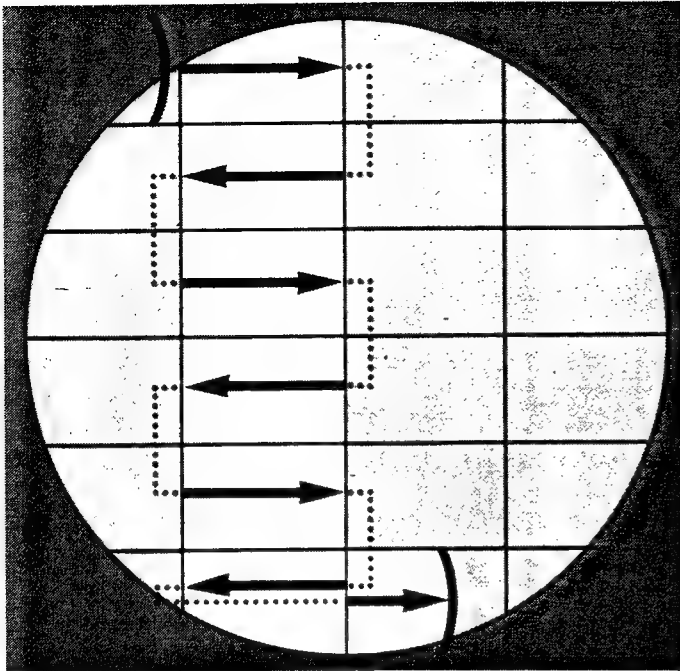
Presentation 4.3.1.2.2-11

The Step-and-Scan Principle

control of exposure, alignment, and focus (see Presentation 4.3.1.2.2-12). Throughputs are maintained with the on-the-fly exposure because the stage never stops. Consequently, there is no settling time. CDs are better controlled because on-the-fly focusing and alignment provides a virtual in increase the depth of field.

The key disadvantage of step-and-scan lies in its optical and mechanical complexity. While the optical assembly has 17 elements in contrast with 20 for a conventional stepper, accurate assembly is difficult because of their awkward positions (see Presentation 4.3.1.2.2-13). Consequently, early systems were difficult to build in volume and field reliability was poor.

The **Markle-Dyson** method is the most recently developed optical technology for DUV lithography. It was developed by David Markle as a second generation to the Wynne-Dyson optical assembly originally developed by Ultratech in the early eighties. Its primary advantage is the elegant simplicity of its optics (see Presentation 4.3.1.2.2-14). The Markle-Dyson optical assembly offers a catadioptric system with only three elements. Consequently, it is the least expensive to produce of all three technologies. However, it is the most immature of all three technologies. Other issues that have yet to be resolved are its lack of a reduction ratio to ease mask making complexity, and its use of reflective masks.

X-ray technology has been at the bleeding edge of lithography since its invention in 1972 by Hank Smith at M.I.T. It has been considered so important, that companies and governments have sunk well over a billion dollars into its development. Its promise lies in the fact that X-rays offer the smallest wavelength of light for lithography. Consequently, it has the potential to achieve resolutions down to 0.1 μm. X-ray lithography can also be characterized by its excellent CD control, superior depth of focus, and its ability to project through surface contamination on wafers and masks. Unfortunately, X-ray lithography has proven to be an extremely difficult technology to implement in production. Mask technology has been a significant barrier to production application of X-ray lithography. While materials are readily available, E-beam lithography, inspection, and repair tools have tremendous difficulty producing 1X masks at 0.1 micron resolutions and 0.035 micron registration. This implies an accuracy of only a few hundred angstroms for inspection tools. Consequently, practical X-ray lithography on ICs is typically done in optical resolution ranges. Work with sub-optical resolution tends to be limited to simple patterns on blank wafers. The need for moderate cost illuminators with high
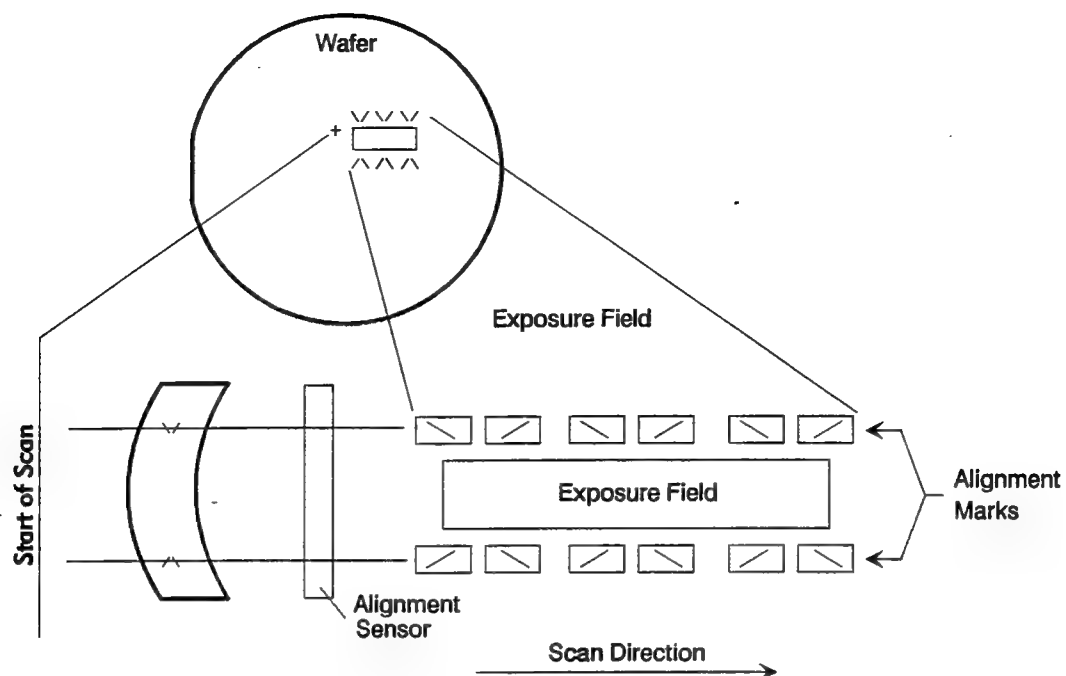
Presentation 4.3.1.2.2-12

Step and Scan Alignment Principle
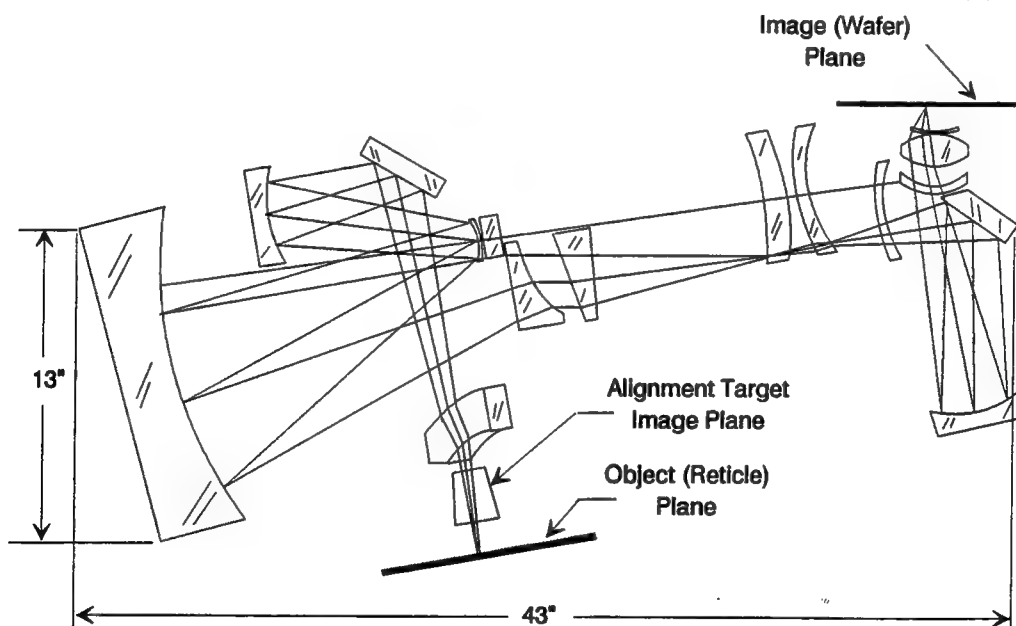
Presentation 4.3.1.2.2-13

Step & Scan Projection Optics

VLSI RESEARCH INC

4.3.1 38
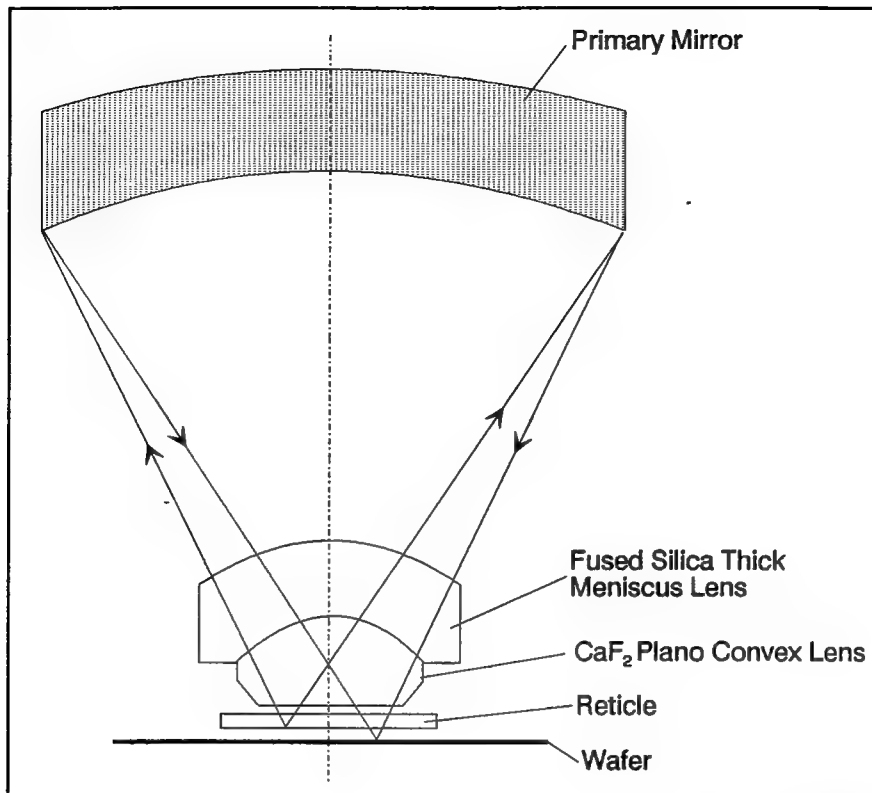
Source: Ultratech
2244-406D

Presentation 4.3.1.2.2-14

Markle-Dyson Projection Optics

output and broad, collimated light are an also issue for X-ray. As is the need for a lensing method.

There are three types of illuminators for X-ray: Tubes, Laser Plasma, and Synchrotron. Tubes are seldom used because their output is so low (less than 0.15 mW/CM²) and they are a point source (see Presentation 4.3.1.2.2-15). Point sources are a problem because they cause penumbral and diffraction blurs, thereby limiting resolution.

Laser plasma illuminators are a substantial improvement over X-ray tubes (see Presentation 4.3.1.2.2-16). They offer almost two orders of magnitude greater exposure power
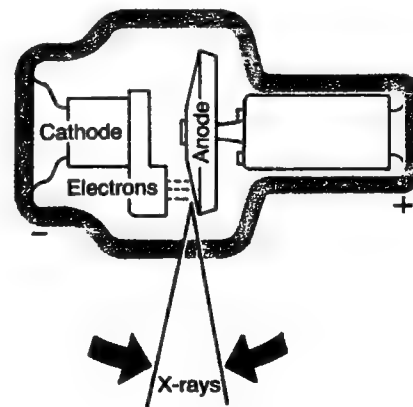
Source: Semi Intl, Sept '83
2244-407

Presentation 4.3.1.2.2-15

Conventional X-Ray Tube

Focused laser pulse creates an X-ray-emitting micro plasma

Cone of x-rays expose the wafer through the reticle or mask.

Retractable optic provides through-the-reticle alignment for 0.14μm (3σ) total registration error.

All exposures take place in atmospheric helium environment.

Gold-on-silicon X-ray reticle has greater than 15:1 contrast ratio.

Independently programmable aperture blades are positioned to define an exposure field up to 20x20mm.

Gas probes measure wafer surface profile as part of patented GapLock ™ algorithm.

Vacuum pin chuck accepts 76 to 150mm wafers.

Source: Hampshire Instruments
2244-408

Presentation 4.3.1.2.2-16

Pulsed Laser Plasma X-Ray Source

(5-15 mW/CM^2). They also offer advantages over synchrotrons in their ability to achieve economies of scale at relatively low capacities. Laser plasma X-ray aligne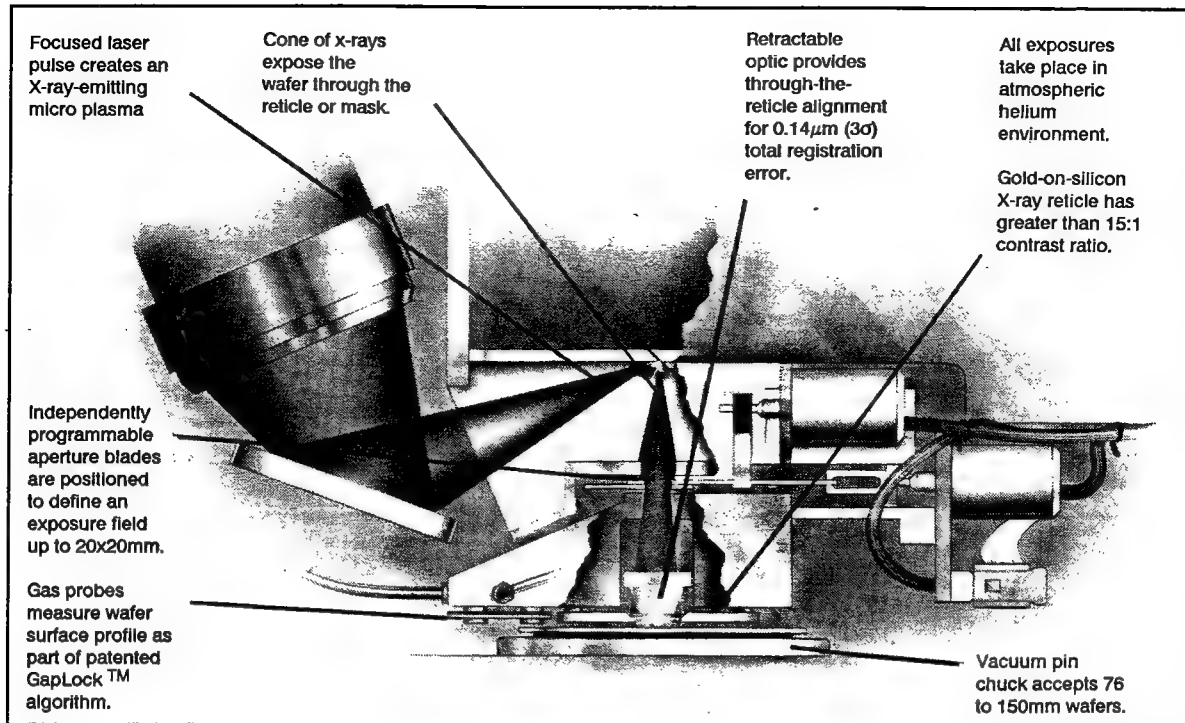rs can be purchased one-at-a-time. Initial investments can be as small as a few million dollars. In contrast synchrotron illuminators have energy outputs that require ten or twenty steppers to be cost effective. Initial investment levels are tens of millions of dollars and cost effective investments are well over $50M.

The primary limitations of pulsed laser plasma sources is their point source characteristic. Run-out error alone reaches one micron when a 20 mm field size is used. Consequently, die sizes are limited when proximity printing is used. This also reduces throughputs since only the 'sweet-spot' of the field can be used.

Even though the entry price is high, synchrotrons do offer a cost effective solution to the problems encountered with proximity X-ray lithography (see Presentation 4.3.1.2.2-17). This is because the working distance between the source and wafer is five meters. Total RMS error due to proximity effects is 0.08 microns for a 20 mm field. Sychrotrons make large field, deep sub-micron lithography achievable with X-ray (see Presentation 4.3.1.2.2-18).

Synchrotrons produce X-rays by deflecting electrons which are traveling at close to the speed of light. Sumitomo provides a good explanation of how this works (see Presentation 4.3.1.2.2-19). The heart of a synchrotron is a circular shaped accelerator. Beams of X-rays are channeled into long tubes called beamlines that project radially from the core. Each emit collimated, parallel beams. The long beamlines serve to reduce

Presentation 4.3.1.2.2-17

Typical X-Ray Proximity Steppers

	X-Ray Tube	Laser Plasma	Synchrotron
General Parameters			
Av. Irradiance (mW/cm^2)	1	10-30	50
Wavelength (nm)	0.4-1.0	1.4	0.5-1.5
Exposing Power (mW/cm^2)	0.005-0.15	5-15	25
Field Size (mm)	40 x 40	20 x 20	25 x 25
Source Diameter (mm)	1	0.05-0.2	0.5
Working Distance (mm)	400	100	5000
Wafer Gap (μm)	40	20-50	10-30
Errors from Proximity Effects[†]			
Penumbral Blur (μm)	0.200	0.025	0.001
Diffraction Blur (μm)	0.140	0.118	0.071
Run Out Error (μm)	2.0	1.0	0.026
RMS Error (μm)	2.015	1.007	0.082
Capital Effectiveness			
Throughput (WPH)	4	20	800[††]
Cost ($M)	NA	4	62
$K/W	-	200	78

[†] *Minimum wafer gap setting with a 20 mm field.*
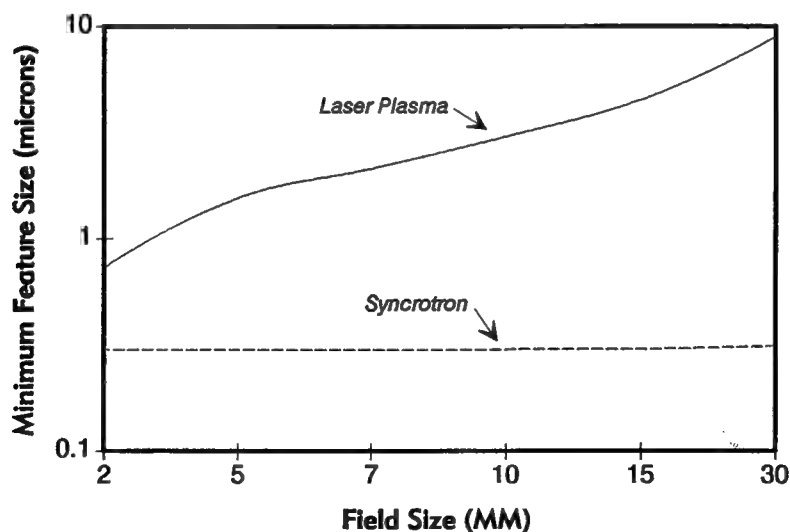[††] *16 beamlines with 16 steppers at $2M each.*

Source: VLSI RESEARCH INC
2244-409W

Presentation 4.3.1.2.2-18

Proximity Effects on X-Ray Resolution [†]

Source: VLSI RESEARCH INC
2244-410G

[†] RMS value of run out error, penumbral blur, diffraction blur, and tool registration times a safety factor of three.

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Presentation 4.3.1.2.2-19

Principle of a Synchrotron

Super-Compact SR Ring AURORA

Synchrotron Radiation (S R) is the electro-magnetic radiation generated when electrons, travelling at speeds approaching the speed of light, are deflected. The radiation is almost entirely composed of X-rays and, because of the nature of the source, the X-ray beams have a much greater intensity than those produced by conventional apparatus.

This high-intensity beam is particularly applicable to the manufacture of future generations of L S I (Large Scale Integrated Circuits), however it is also applicable to the field of medical research and in the analysis of macromolecular structures.

Until now, the S R Ring has been so large that its commercial applications have not been appropriate for its installation requirements, and there has been considerable demand for a more compact model. Sumitomo Heavy Industries is now able to offer the AURORA, the world's smallest S R Ring to meet those demands.

The AURORA S R Ring

The AURORA, developed by S H I, is composed of three sections, namely; the Microtron Injector, the Storage Ring, and the Beam Guides.

The Microtron Injector

This injector is capable of accelerating electrons up to an energy of 150 MeV.

It is a compact unit, developed to take the place of the current Linac Accelerator, and having, apart from its considerable space-saving, the advantage of generating a beam of greater cohesion, thus allowing reduced shielding while at the same time minimizing beam losses during injection into the Storage Ring.
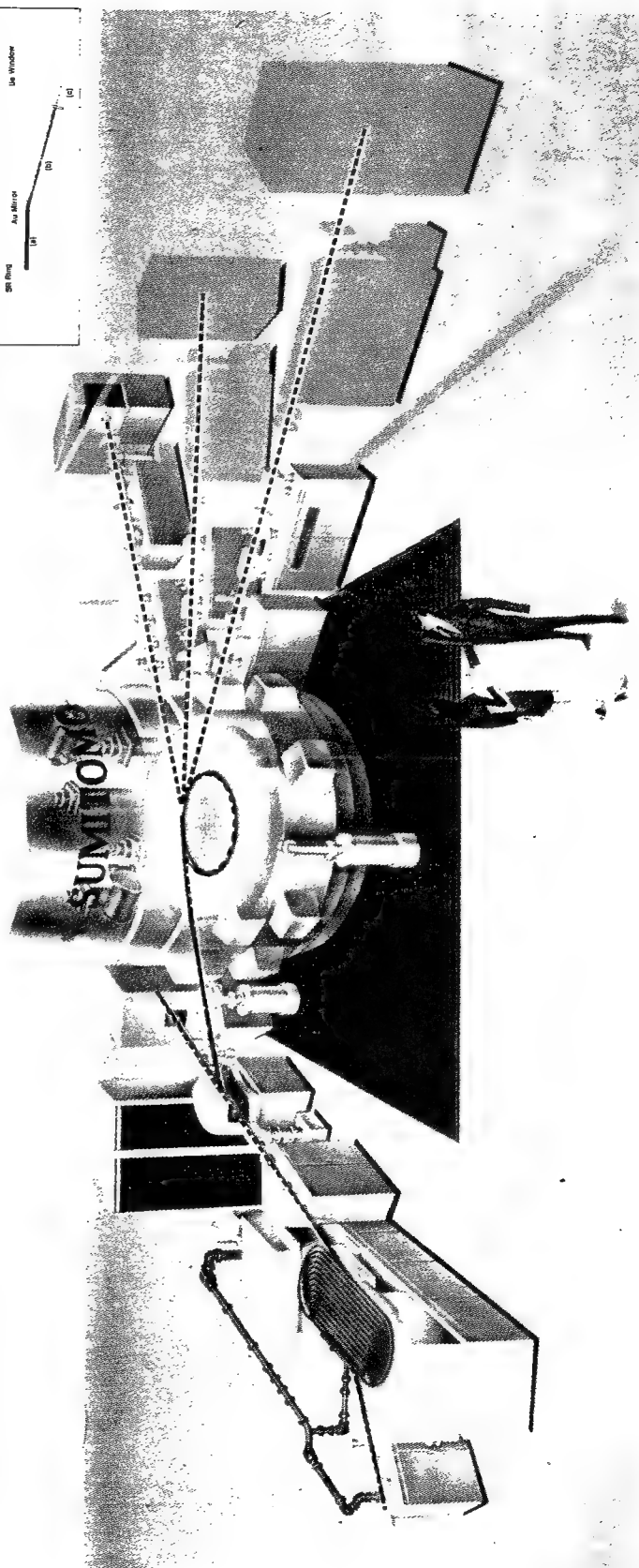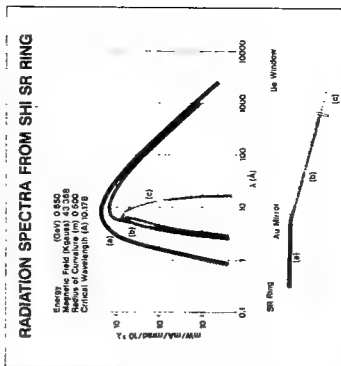
The Storage Ring

The electrons, accelerated to 150 MeV in the Microtron, are injected into the Storage Ring. In the Storage Ring the electrons, orbiting in a circular path of 1 metre diameter, are accelerated up to an energy of 650 MeV and generate the desired Synchrotron Radiation.

The Storage Ring itself is composed of a single superconducting magnet and is contained within a solid iron yoke of 3 meters outer diameter. This iron yoke provides adequate shielding from radiation and any stray magnetic fields.

One of the problems of such a Storage Ring has been in the injection of the electron beam into the circular orbit. S H I has overcome this problem by the use of the "Half Integer Resonance Injection Method" also developed by S H I which enables electron injection into single-magnet systems.

The Beam Lines

A maximum of 16 S R beams can be directed from the Storage Ring. These guides are used not only to guide the S R beams, but also to adjust the energy spectrum of the beams as shown in the following figure. Each guide also incorporates several safety devices to protect the integrity of the vacuum within the Storage Ring.
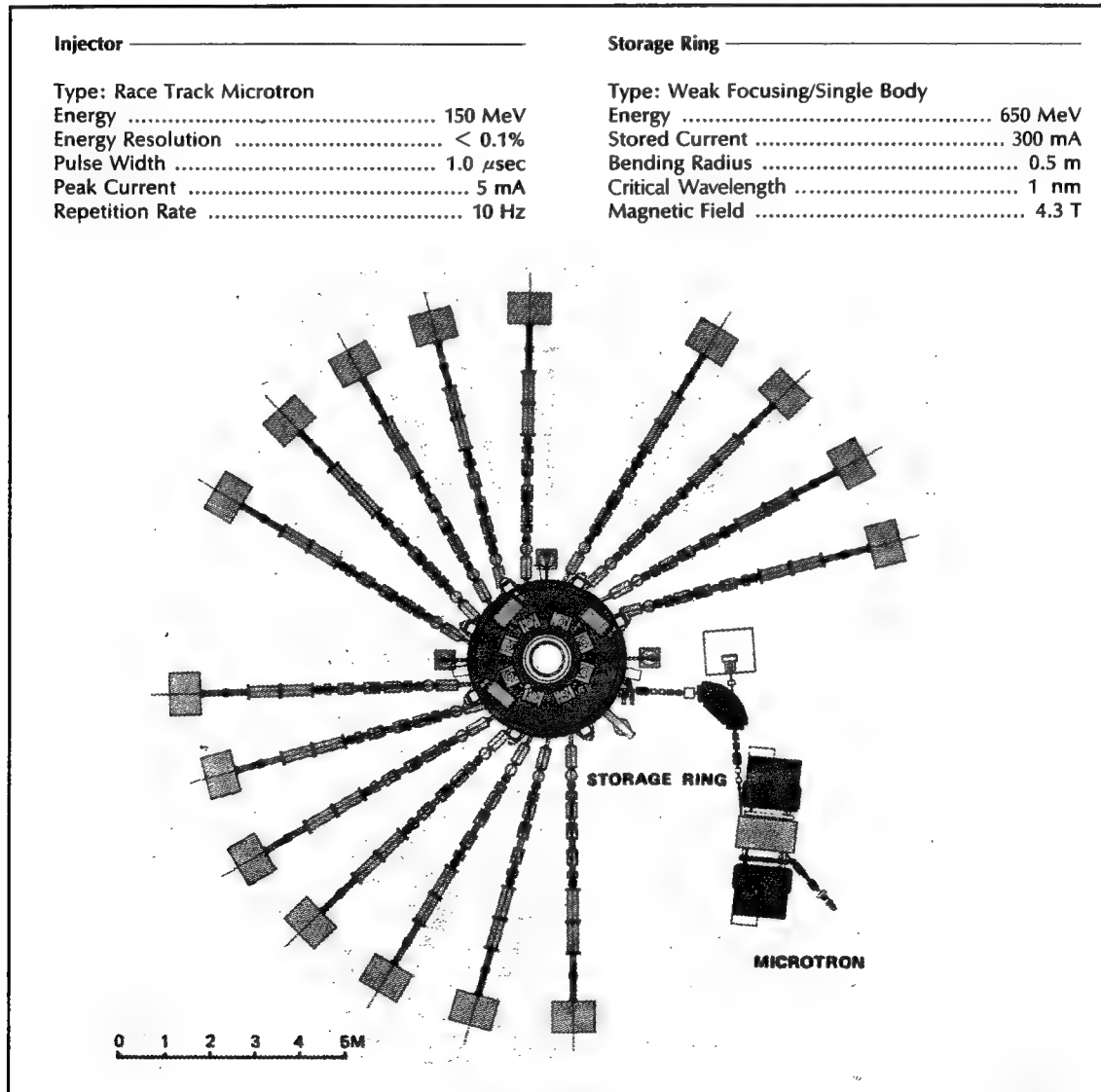

RADIATION SPECTRA FROM SHI SR RING

Energy (Gev) 0.650
Magnetic Field (kGauss) 43.388
Radius of Curvature (m) 0.500
Critical Wavelength (Å) 10.078

proximity effects significantly. The synchrotron also produces the brightest X-rays of all modern sources, which gives it relatively high throughputs. Because of this energy, one source can be used for up to 20 steppers.

However, the synchrotron does have many issues that limit its use. Most important of these is its size. Presentation 4.3.1.2.2-20 depicts a fully loaded synchrotron lithography bay. It is clear that wafer fab's would have to be completely designed around it. Moreover, its high capital costs and high incremental capacity, limit it to large commodity markets such as DRAMs. Its high power causes radiation damage to masks-shortening their life. Reliability and qualification are also a concern. Synchrotrons can take one day or more to bring-up because

Injector ———————————————

Type: Race Track Microtron
Energy .... 150 MeV
Energy Resolution .... < 0.1%
Pulse Width .... 1.0 μsec
Peak Current .... 5 mA
Repetition Rate .... 10 Hz

Storage Ring ———————————————

Type: Weak Focusing/Single Body
Energy .... 650 MeV
Stored Current .... 300 mA
Bending Radius .... 0.5 m
Critical Wavelength .... 1 nm
Magnetic Field .... 4.3 T

STORAGE RING

MICROTRON

0 1 2 3 4 5M

Source: Sumitomo Heavy Industries, LTD
2244-412

Presentation 4.3.1.2.2-20

Synchrotron Layout

they operate at 10^{-9} torr or greater and beam lifetimes are only 24 hours. Most importantly, synchrotrons are unproven and so few companies feel comfortable considering it as a production tool.

Nevertheless, the fundamental problem with X-ray lithography today is its use of proximity printing. This has lead researchers to examine ways to achieve projection lithography using soft X-rays.

Soft X-ray projection lithography (commonly referred to as XPL) uses reflective optics. Soft X-rays are normally defined as being in 5-20 nanometer (nm) range as contrasted with hard X-rays in the 0.5 to 2.0 nm range. Light wavelengths of 10-15 nm are most typical for lithography applications. Soft X-rays are not as damaging and they reflect better. Work with soft X-rays has led to the development working lenses that serve as test beds for XPL.

XPL lenses use a multi-layered sandwich of thin films, called "Bragg diffractors". These layers form an X-ray mirror when their period is roughly half the wavelength used. It is currently possible to manufacture reduction X-ray lenses that reflect up to 60% of light wavelengths between 13 and 15 nm. GCA Tropel and AT&T have developed an off-axis Schwarzschild XPL test-bed (shown in Presentation 4.3.1.2.2-21). It is a 20:1 reduction camera used for R&D purposes only. This approach is similar to Nikon's work with NTT in Japan. These types of lenses have shown an ability to print 0.05 micron lines and spaces. Consequently, 0.1 micron production lithography should be achievable if these test-beds can be scaled-up to production systems.

The difficulty in manufacturing such a system will lie in the precision required. Lens uniformity will need to be within 0.7 nm, in order to conform to the optics design rule of a twentieth of a wave. Surface roughness will be only a few angstroms. It

is currently impossible to build a large-field spherical lens that would meet the specification needed in a production aligner. The polishing and measuring methods have yet to be developed. Nevertheless, it is considered feasible that scanning reduction XPL systems for production will be available by the early part of the next century.
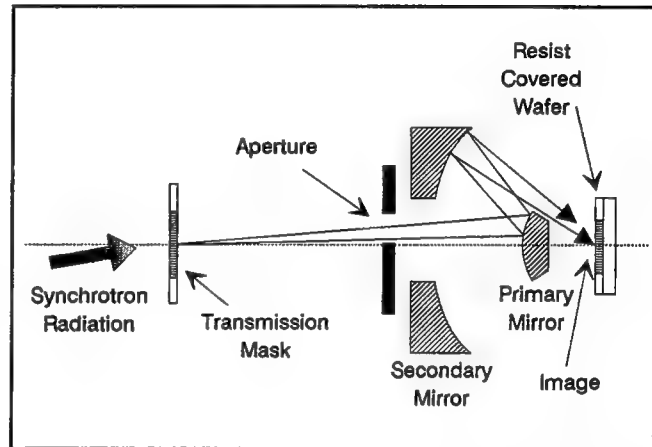
Source: GCA Tropel
2244-413D

Presentation 4.3.1.2.2-21

Schwarzschild X-ray Projection Lenses
(20:1 reduction)

4.3.1.2.3   Mask Making Technology

Mask making is an integral part of the lithography operation. The mask patterning must be extremely precise in order for an image projected onto a wafer to be accurately placed. The procedure of mask making involves the transfer of specific CAD designs into a physical layout to create a geometrical pattern. Coordinates of the IC layout are digitized and stored on tapes. The pattern is then transferred onto the surface of chrome-quartz plates. The mask making process consists of two technological segments—pattern generation and photorepeating.

Pattern generation is the heart of mask making. It is the process of engraving the circuit pattern onto a chrome covered quartz plate creating a reticle pattern. Four methods of pattern generation exist: optical, E-beam, focused ion beam and laser beam.

Optical pattern generation uses light focused through lenses and apertures to create the circuit patterns on the mask. This procedure uses stored digital patterns to drive a computer controlled variable aperture, thus exposing the resist. The system reads a tape and adjusts apertures to expose a reticle with the same pattern as the digitized IC layout. Limitations in resolution and throughput obsoleted these systems in mid-eighties.

E-beam pattern generation is the most commonly used system in mask production today. It is used in both mask production and wafer exposure. There are two methods used for beam scanning: Raster and Vector. The raster scanning technique is more often used for mask making. Vector scanning is more often used for wafer exposure. Both are covered here, since they are technically similar.
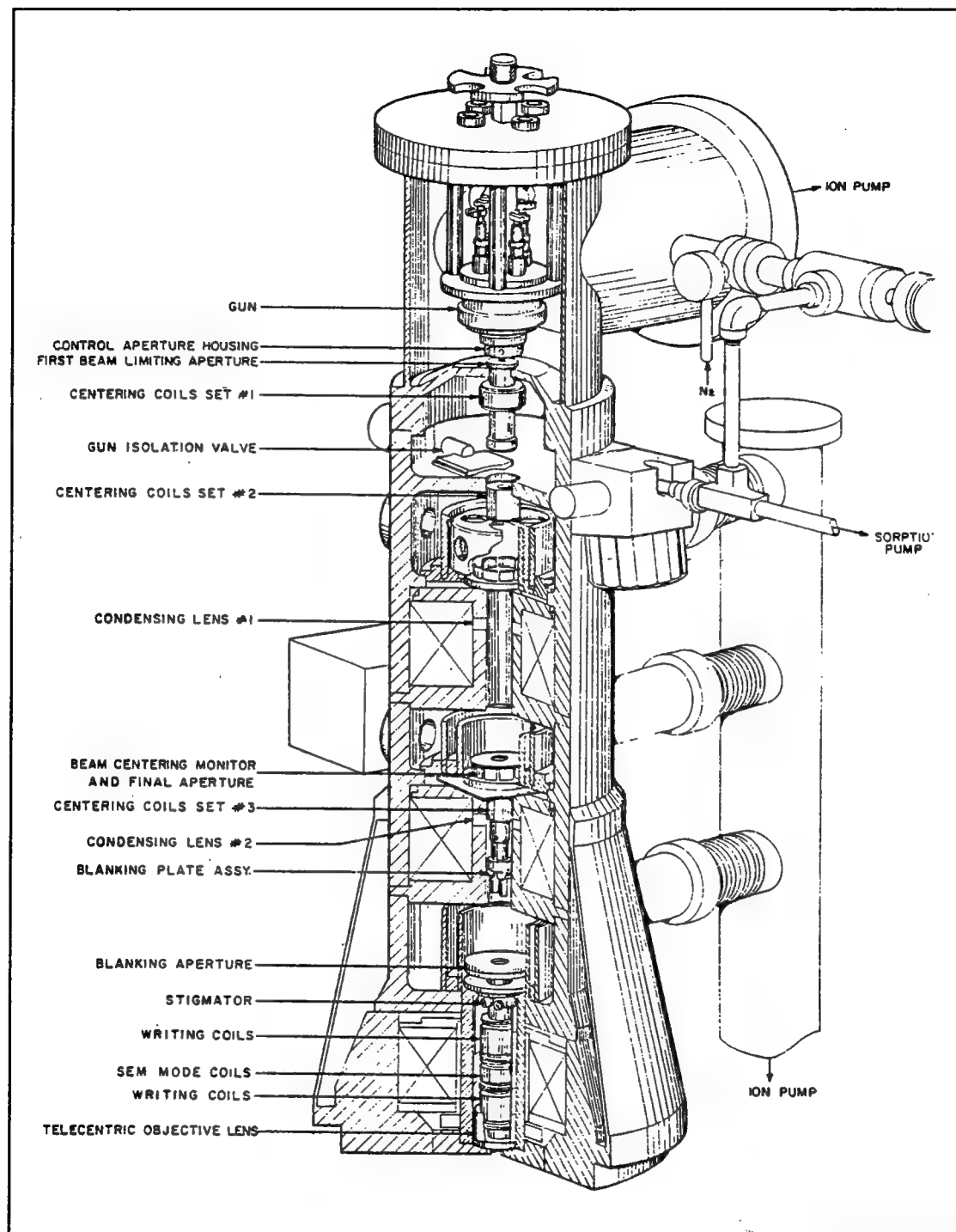
With raster scanning, each pixel in a field is exposed as the beam is scanned back and forth by the electron optics. The beam is simply turned on and off to expose needed pixels on a substrate. This method makes it easier to scale designs to smaller dimensions, because spot sizes are all that need to be reduced since it is a bit map image.

But, raster scanning is not as fast as vector scanning. As device complexity rises, the time it takes to write a mask increases. Defects generated during exposures that exceed several hours makes masks virtually unusable. Device complexities can reach a point where raster scanning is too slow to make usable reticles. Consequently, attention turns to vector scanning.

The vector scanning technique is more like a small floodlight than a pencil beam. It moves the beam on a vector path that directly exposes the entire regions needed, and the beam is turned-on and the pattern is written. The beam is then turned-off and repositioned over another pattern for exposure. It is faster because the beam wastes no time rastering over areas that don't need exposure. However, it is more difficult to scale since all vectors must be recalculated to reduce size.

All E-beam lithography systems employ an electron gun, and a complex series of electron optic elements to direct the beam (shown in Presentation 4.3.1.2.3-1). The electron gun use in an E-beam column is similar to ones found in a common television tube. The optical components in the column include centering coils, electromagnetic lenses, beam blanking plates, a stigmator, and scanning coils. Presentation 4.3.1.2.3-2 depicts each of these graphically. Centering coils center the beam and maximize electron transmission through the column. Electromagnetic lenses concentrate the beam. The electrostatic beam blanking plates and the aperture turn the beam on and off as it scans. This works by deflecting the beam onto the aperture whenever the plates are energized, thereby blanking it off. Otherwise, the beam passes through the column. The stigmator is used to remove astigmatisms in the beam. The scanning coils, along with the final lens moves the beam so that it can be placed accurately.

Columns for vector scan systems are essentially the same as those used in a raster scan system. The primary difference is that the most sophisticated vector scan systems use a variable shaped beam to enhance throughput. This requires additional apertures and a shaping deflector (see Presentation 4.3.1.2.3-3). This allows the column to tailor the beam shape so that it fills a full pattern, thereby eliminating edge scalloping. It also improves throughput significantly

GUN

CONTROL APERTURE HOUSING
FIRST BEAM LIMITING APERTURE

CENTERING COILS SET #1

GUN ISOLATION VALVE

CENTERING COILS SET #2

CONDENSING LENS #1

BEAM CENTERING MONITOR
AND FINAL APERTURE
CENTERING COILS SET #3

CONDENSING LENS #2

BLANKING PLATE ASSY.

BLANKING APERTURE

STIGMATOR

WRITING COILS

SEM MODE COILS

WRITING COILS

TELECENTRIC OBJECTIVE LENS

ION PUMP

N₂

SORPTION PUMP

ION PUMP

Source: Varian
2244-414

Presentation 4.3.1.2.3-1

Typical E-Beam Lithography Column

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4.3.1   46
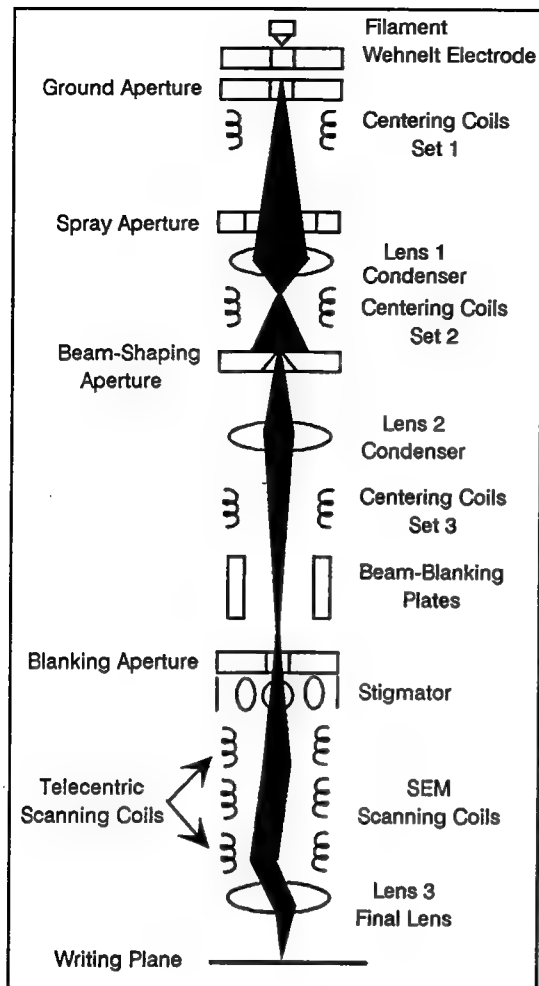
Source: Varian
2244-415D

Presentation 4.3.1.2.3-2

Path of an E-Beam Column

scanning axes. However, this technique reduces the throughput of E-beam systems, since each square segment of a line contains sixteen 'spots' to be exposed. The computer control system of an E-beam system can also be a source of low throughputs. The computer must transfer so much information to operate an E-beam system, that it can bog down, further reducing throughputs.

Vector scan systems are inherently faster than are raster scan systems. However, their acceptance has been slow because of

Source: JEOL
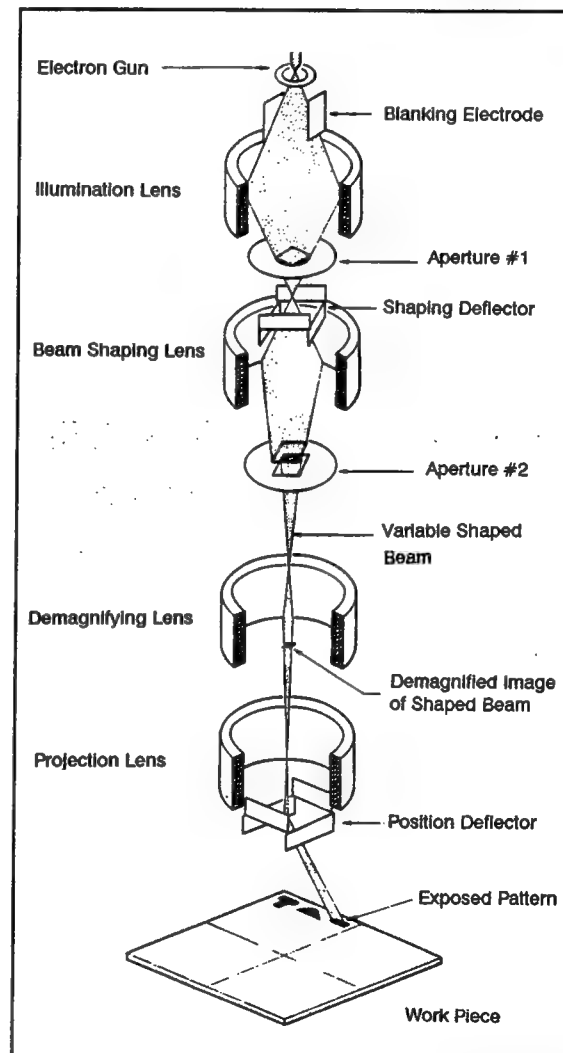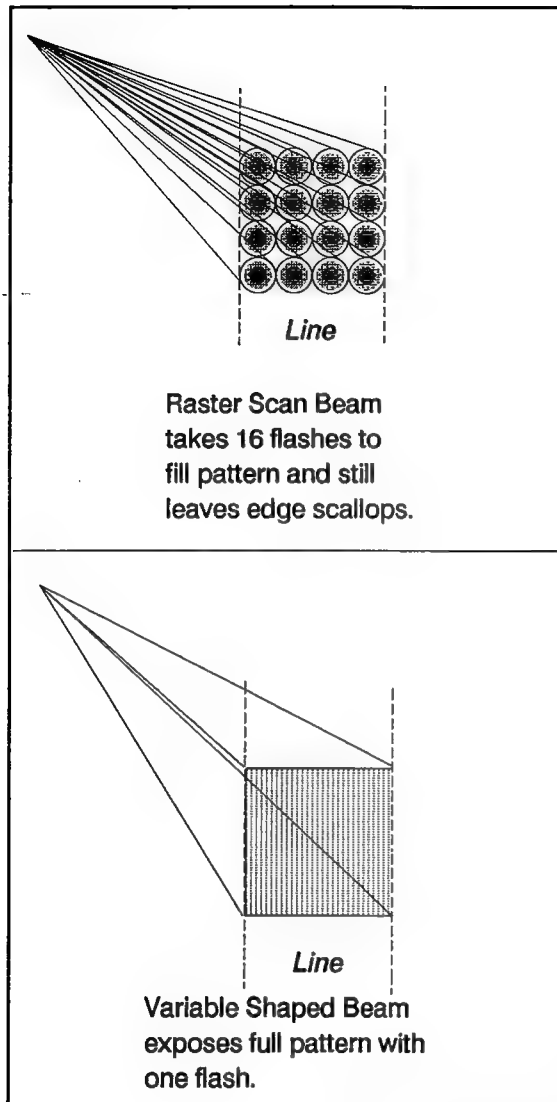2244-416

Presentation 4.3.1.2.3-3

Vector Scan, Variable Shaped E-Beam Column

over a raster scan system because only one flash is needed to fill a square pattern. Presentation 4.3.1.2.3-4 shows how this works.

Throughput is the most critical problem with E-beam systems. This is exacerbated with raster scan systems because the beam spot size is reduced to one-quarter of a linewidth. This is done to maintain sharp edges and to avoid 'scalloping' on those lines which angle off from the two principal

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Raster Scan Beam
takes 16 flashes to
fill pattern and still
leaves edge scallops.

Variable Shaped Beam
exposes full pattern with
one flash.

Source: VLSI RESEARCH INC
2244-417D

Presentation 4.3.1.2.3-4

Vector Scan Versus Raster Scan

the software issues involved in programming them. Raster scan systems are inherently easier to program because the image is simply pixelated with each pixel having a coordinate. As the beam scans in a fixed direction, it is turned off and on as needed. Devices can be scaled by simply changing the pixel size. In contrast, vector scan systems require that the beam be specifically programmed for each path that it must

expose. Changes in mask dimensions require a complete recalculation of all beam paths and sizes. Consequently, software has always been a key limiting factor for vector scan systems. Nevertheless as computer power continues to increase, this issue becomes easier to resolve. Consequently, the natural rise in all device's complexity, leading to greater computing power, makes it inevitable that vector scan will replace raster scan. When that day comes, the most important competitive asset will be a company's software capability.

Ion beams and laser beams can also be used to either direct write a wafer or expose a mask. These systems are very similar to E-beam, with the main exception being their use of lasers or ions rather than electrons. Ion beam pattern generators are not common. Ion beam technology is used more in the measurement field.

Laser beam pattern generators use the raster scanning method. They gained rapid popularity because they tend to be faster and more accurate than E-beam systems. They are also less expensive as well. Laser beams are more accurate than E-beams because they are more stable. Electrons are very sensitive to magnetic fields and they tend to scatter. However, the main limitation of laser lithography is resolution. Laser beams have the same optical limits as those discussed in the previous section.

Presentation 4.3.1.2.3-5 shows a typical laser pattern generator. The laser beam split into several beams which expose several spots on the wafer at a time to enhance throughput. The modulator performs the same tasks as the blanking mechanism in an E-beam system. It uses an Acousto-Optical lens to turn each beam off and on. The rasterizer engine controls the modulator. The steering mirror deflects the laser beam towards the zoom optics. It also adjusts for fluctuations in relative positions of the beam, polygonal mirror and reticle stage. Zoom optics con-

Source: ETEC
2244-418D
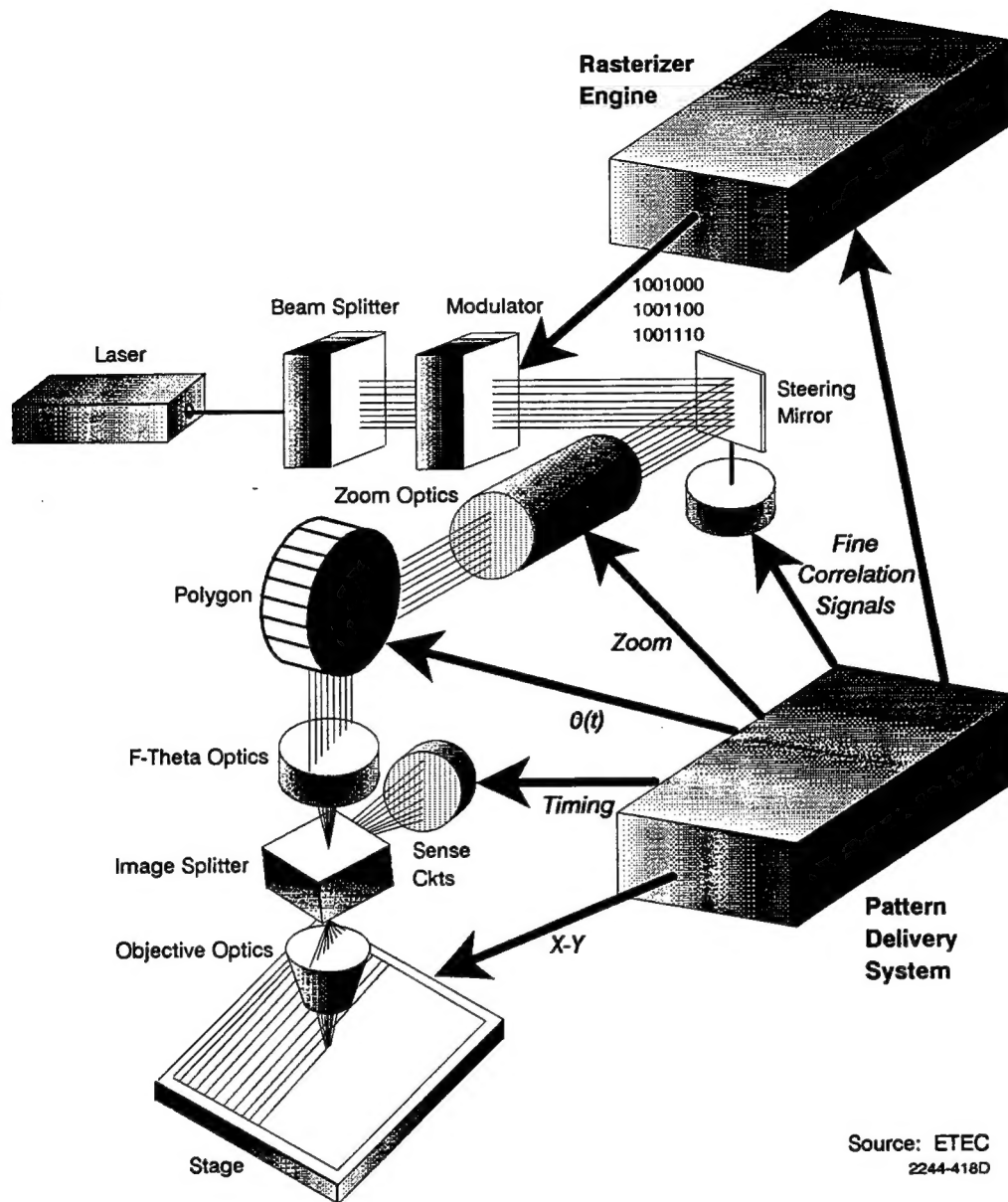
Presentation 4.3.1.2.3-5

Laser Pattern Generator Architecture
(Core-2000 reticle writer)

trol beam spot size. The rotating polygon drives the beam in a scanning motion. Each facet passing across the beam creates a single horizontal scan. Consequently, it must rotate at very high speeds. The F-theta optics converts the polygon's output to linear scan across the reticle. These beams then pass through an image splitter and 10X reduction optics before it exposes the reticle.

Both E-beam and laser beam pattern generators are well established in the market. There are no perceivable trends in equipment that will upset their position in the foreseeable future. The key technical driving forces will be the continued reduction of linewidth and registration requirements. The advent of phase-shift masks will accelerate these needs if they prove successful in the market.

Phase-shift masking technology lay dormant for many years after its discovery in 1980 by Hank Smith and Dale Flanders of MIT. Independently, work at IBM lead to the publication of Marc Levinson's landmark paper on the subject in 1982. But, the technology was considered by many to be too complex and unnecessary. However, it

gained renewed interest in the late eighties as problems with excimer laser steppers and X-ray began to mount. Several Japanese companies began to research it with hopes of extending I-line technology to the 64 Mbit DRAM. By the early nineties, phase-shift masks became viewed as a basic technology that could extend linewidth capabilities for all optical aligners, including X-ray.

The essence of phase-shift mask technology is described in Presentation 4.3.1.2.3-6. It is well-known that light develops interference when exposed through a conventional mask with tight lines and spaces. The amplitude of light on the wafer blends. The resulting positive intensity across the wafer causes some exposure in unintended areas of resist. The result is blurred lines and spaces.
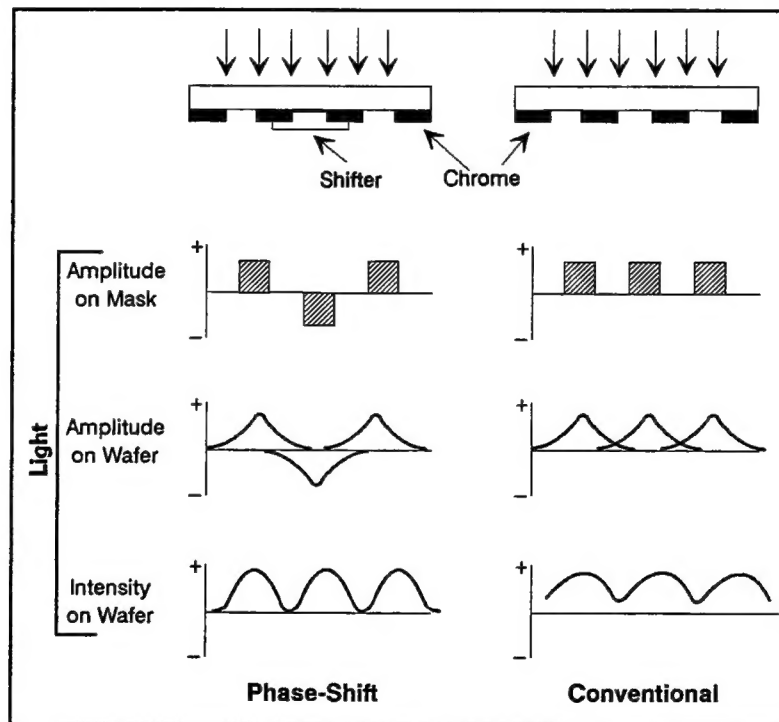
Source: VLSI RESEARCH INC
2244-419D

Presentation 4.3.1.2.3-6

Phase-Shift Mask Technology Basics

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4.3.1 50

Phase-shifting adds a translucent film that shifts light amplitude of the center mask window to the opposite phase. Consequently, the interference is eliminated and the light intensity falls to zero under chrome areas. The result is clearly defined lines and spaces.

There are many types of phase-shift masks in use today. The most common are alternating phase-shift gratings, 0/90/180 degree phase-shift masks, and chromeless phase-shift masks. The alternating phase-shift grating was the original PSM used by Levinson and was shown in the previous presentation. It uses a conventional chrome mask with phase-shifting films applied on every other window.

Photoresist is typically used as the phase shifter. This method creates a 0 to 180 degree phase-shift between patterns. The key issue with this method is the creation of a 'zero node' in phase transition between 0-180 degrees. Consequently, this led researchers to an alternating phase-shift mask with a phase-shift of 0, 90, and 180 degrees. However, intensity nulls still create unwanted fine lines. This led researchers to develop a chromeless phase-shift mask. This type provides a better exposure on the wafer and it eliminates the need for a second alignment on the mask. However, the chromeless method pushes E-beam pattern generators to their technical limits and beyond. Requirements include resolutions of 0.5μ, registration of 0.05 microns, corner rounding to 0.1 micron, and CD control of 0.0125 microns. Nevertheless, these technical requirements are achievable. Consequently, phase-shift masking will continue to develop as a production tool.

Notes